

# Arizona Geological Survey

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## Plate Tectonics and the Gulf of California Region

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Figure 1. Satellite photo of the northern Gulf of California region. C = Colorado River delta; K = Kino Bay (Bahía Kino); P = Pinacate volcanic field (Sierra Pinacate); R = Rocky Point (Puerto Peñasco); S = Salton Sea; Y = Yuma.

The Gulf of California, familiar to many Arizonans as a recreation mecca and important part of Mexico's fishing and tourist industries, is unusual in terms of its depth, tidal range, salinity, temperature, and marine life. Many of the singular features of the Gulf of California (also known as the Sea of Cortez) may be explained by its shape and bottom profile, both of which are reflections of the gulf's geologic history. This article summarizes the unique features of the gulf, describes the theory of plate tectonics, explains how tectonics may have affected the geologic evolution and physiography of the gulf, and illustrates the process by which the Colorado River became linked to the gulf.

### Natural Features of the Gulf

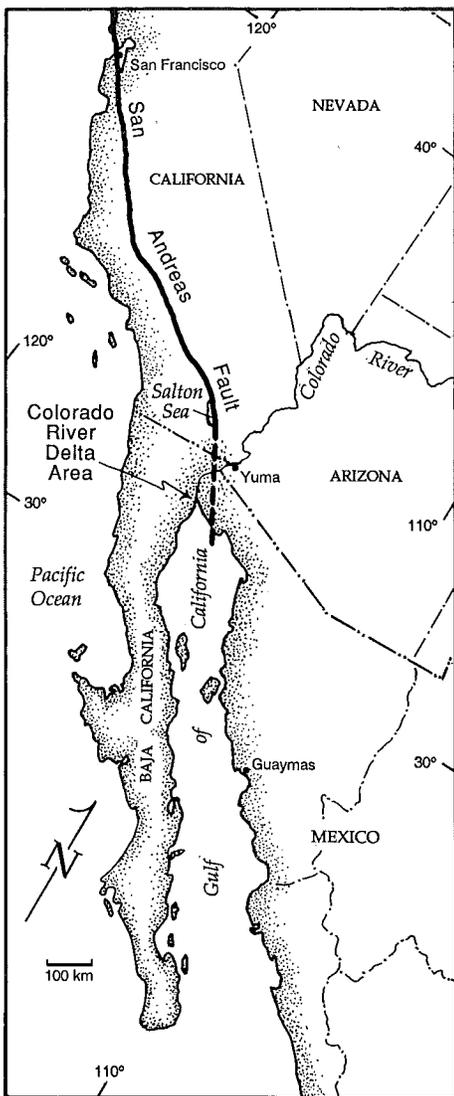
The Gulf of California is approximately 1,100 kilometers in length and ranges from 48 to 241 kilometers in width (Figures 1 and 2). Its long and narrow shape influences its tidal range, which is the third highest in the world and can reach almost 10 meters in the northern section (Flessa and Eckdale, 1987). The shape of the gulf is analogous to a bathtub, and the tides, which are greatest at the northern and southern ends and almost nonexistent in the middle, resemble water in a bathtub that sloshes back and forth when disturbed.

The high salinities and temperatures of the shallow water in the gulf are partially due to its shape, which restricts interchange of water between the gulf and Pacific Ocean. Salinities vary from 36 to 39 parts per thousand. (The salinity of normal seawater is approximately 35 parts per thousand.) In the northern gulf, surface water temperatures range from approximately 31° in the summer to 11° in the winter (Brusca, 1980). The depth of the gulf also affects temperature and salinity by increasing heating and evaporation rates. The gulf is shallow (generally less than 200 meters) at its northern end but deepens to the south. Parts of the southern two-thirds of the gulf range from 2,400 to 3,600 meters in depth, with troughs plunging as deep as 4,060 meters (Brusca, 1980). Several shallower troughs are also present in the northern section close to the Baja California coastline. The edges of these troughs are the sites of upwelling, which brings cold nutrient-rich water to the surface. The organisms that feed upon the nutrients attract, directly or indirectly, a wide variety of other animals, including shrimp, tuna, whales, dolphins, sea lions, sharks, sea birds, and humans.

### Plate-Tectonic Theory

The Gulf of California began to form 4 to 6 million years (m.y.) ago during the late Miocene as Baja California separated from the Mexican mainland (Moore and Curray, 1982; Stock and Hodges, 1989). The geologic events that forced the gulf open and split off Baja California were driven by global-scale forces. The theory of plate tectonics describes these geologic processes.

The Earth's crust and uppermost mantle, collectively known as the lithosphere, are composed of 8 to 10 large discrete blocks or plates and many smaller plates (Figure 3). The oceanic parts of the plates are 80 to 100 kilometers thick; the continental portions are typically 110 kilometers thick or more (Sawkins and others, 1978).



Each plate moves with respect to the other plates. The boundaries between plates accommodate this motion and are the sites of several types of geologically important processes (Figure 4). Earthquakes, for example, are often associated with tectonic boundaries.

Plates may move apart, leaving a gap (or rift) in between that fills with new molten crustal material. The newly formed crust is hot relative to the crust surrounding it and rises to form ridges (or rises; Figure 4A). Spreading occurs as the new crust is added on either side of the rift, being injected between older crust as the plates move apart. This process occurs in both oceanic and continental crust. Long continuous systems of troughs and ridges characterize spreading areas on oceanic plates. Spreading in continental settings breaks continents apart. The Great African Rift Valley in eastern Africa is an active example of continental rifting.

Driven by spreading forces, plates may move toward one another and collide. One plate may be pushed under another or the plates may slide past each other. Oceanic lithosphere is denser and heavier than continental lithosphere, and consequently the

oceanic plate is generally thrust (subducted) beneath the continent (Figure 4B). Plate destruction and plate formation balance each other, preserving the Earth's total surface area. Plate-tectonic theory suggests that subduction is actively occurring at the boundaries of most oceanic and continental plates in the Pacific Ocean. The Pacific Plate, for example, is being subducted underneath Asia near Japan; the associated melting of this oceanic crust formed the Japanese islands and accounts for the active volcanism in this area. Collision of the Eurasian and Indian Plates, both continental plates, created the Himalaya Mountains as the plates collided and one overrode the other. The resulting mountains are underlain by crust that is approximately twice the average thickness of continental crust.

Plates may also move past one another by shearing along faults that parallel the plates' motion (Figure 4C). This type of interaction along a transform boundary creates large stresses in the Earth's crust. The San Andreas fault represents the boundary between the Pacific and North American Plates, which are moving past each other.

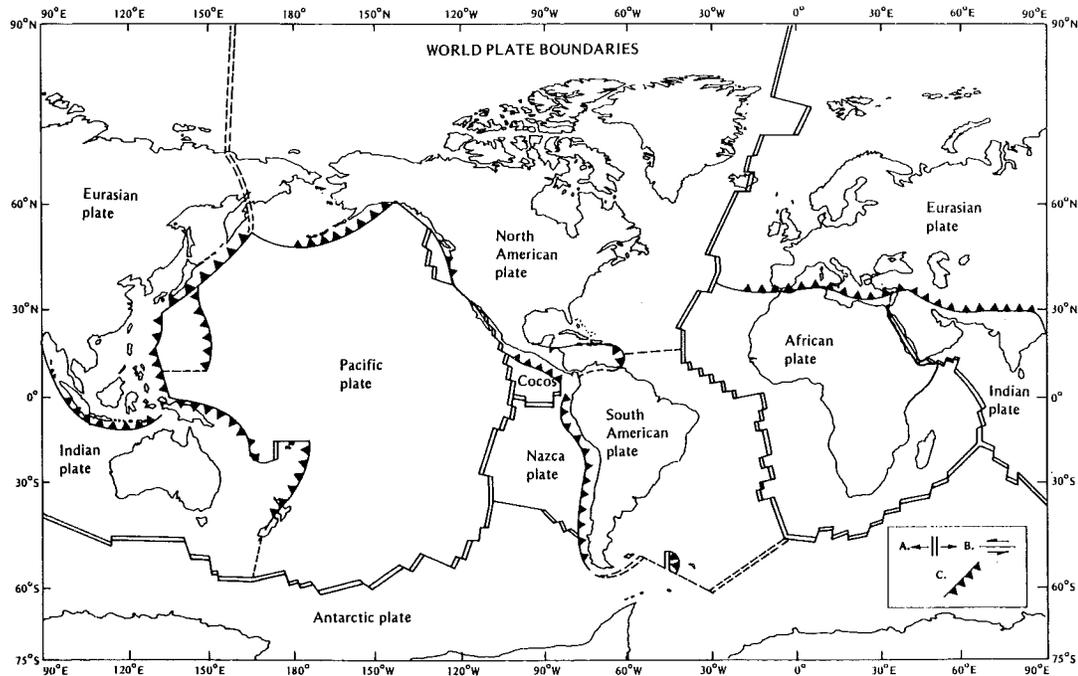
Plate-tectonic theory not only describes the relative motion between crustal plates today, but also provides a useful framework for reconstructing the positions of plates in the past. For example, during the late Paleozoic and early Mesozoic eras, approximately 225 m.y. ago, all of the continents were assembled into one large continent, known as Pangaea. Evidence for the existence of Pangaea comes from many sources, including the distribution of "matching" rocks and fossils of the same age on different continents, the shapes of the continents, and paleomagnetic data.

The *Glossopteris* flora, an assemblage of Permian (286- to 245-m.y.-old) plant fossils, is present in Africa, Australia, India, Madagascar, South America, and Antarctica. Africa and South America fit together like pieces of a puzzle. They formed a single continent that was rifted apart and separated by sea-floor spreading, which created the Atlantic Ocean. Paleomagnetism, the relict magnetism within magnetic minerals in rocks, represents the state of the Earth's magnetic field at the time the rock was formed. The direction of the paleomagnetism may be compared with the magnetic field at other locations and other times. Paleomagnetic data, therefore, may serve as compass needles, allowing geologists to reconstruct the geographical distributions and motions of oceans and continents during the past.

The changing positions of

Figure 2 (left). Location of the Gulf of California, Colorado River, Salton Sea, and San Andreas fault system, which includes several associated faults. Modified from Hamilton, 1961, p. 1309.

Figure 3 (below). Major plates of the world. The types of plate boundaries, marked by heavy lines, are as follows: (A) Mid-oceanic ridges at which the plates move apart are represented by double lines; (B) Transform fault boundaries are shown by single lines; and (C) Trenches and other subduction zones are marked by lines with teeth on one side; the teeth point down the descending slab. Dashed lines are used where the exact location or nature of the boundary is uncertain. From Sawkins and others, 1978, p. 163.



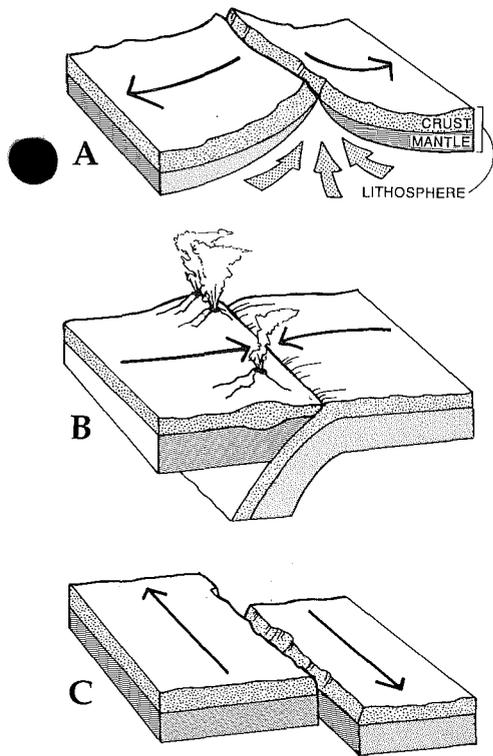


Figure 4. Three types of plate boundaries and relative plate motions. (A) Divergent (plates move away from each other): the process of sea-floor spreading creates new oceanic lithosphere; (B) Convergent (plates approach each other): the process of subduction destroys lithosphere; (C) Transform (plates slide past each other without approaching or diverging): transform faulting is the corresponding process. Modified from Sawkins and others, 1978, p. 165.

crustal plates have affected many of the Earth's systems. The positions of continents and oceans, for example, influence oceanic and atmospheric current patterns. These, in turn, significantly affect global climate. Plate tectonics also plays a role in polar glaciation. Along with periodic, favorable climatic conditions, resulting from changes in the Earth's orbit, the presence of a land mass or continent near or over the pole is necessary for polar glaciation. As polar ice accumulates, sea level drops worldwide and ice sheets spread over the continents.

### Tectonic History of the Gulf

Both the physical characteristics and the origin of the Gulf of California are intimately tied to tectonic processes. The gulf is bounded on the northeast by the North American Plate, which includes the North American continent, and on the southwest by the Pacific Plate, which is currently moving northwest with respect to the North American Plate. The San Andreas fault system is part of the boundary between these two plates. The East Pacific Rise, a spreading system on the Pacific Plate near its boundary with the North American Plate (Figure 3), has been partially subducted underneath the North American Plate during the past 30 m.y. (Atwater, 1970). In the vicinity

of the gulf, subduction occurred on the west side of Baja California, which was then part of the Mexican mainland. Subduction ceased, however, off the Baja coast 10 m.y. ago, and the juncture between the two plates became a transform boundary (Atwater, 1970; Figure 4C). By 6 to 4 m.y. ago the margin strengthened, probably as it cooled and became more rigid, and a weaker inland zone broke to accommodate the shearing motion between the two plates (Atwater, 1970). The shift of this plate margin had two important results: Baja California was ripped off of the North American Plate and became part of the Pacific Plate, and the Gulf of California was created (Atwater, 1970). Both Baja California and a large portion of southern California are now part of the Pacific Plate, which continues to move northwest with respect to the North American Plate. Baja California, in fact, has moved approximately 300 kilometers to the northwest from its original position on the North American Plate (Moore and Curray, 1982).

Reconstruction of the positions of Baja California and the Mexican mainland reveals that a large embayment existed in the continent during the late Miocene (12 to 5 m.y. ago), prior to the opening of the Gulf of California. Evidence for this embayment, known as the "proto-gulf," includes the distribution of marine and nonmarine sedimentary rocks and changes in volcanic patterns that predate rifting (Stock and Hodges, 1989). Several mechanisms have been invoked to explain the existence of the proto-gulf, including Basin and Range extension, which is related to the widespread mountain-forming episode that occurred in Arizona during this time, and extension associated with development of the Pacific-North American Plate boundary (Stock and Hodges, 1989). This extension may have weakened the crust underlying the proto-gulf and facilitated the onset of rifting (Stock and Hodges, 1989).

### Tectonism and Sedimentation Patterns in the Gulf

The spreading center in the Gulf of California does not form a straight line of ridges and troughs because both spreading and transform motion are occurring. This creates a zigzag pattern of troughs and faults (Figure 5). The floor of the gulf contains a series of parallel faults aligned with the motion of the Pacific Plate and separated by small deep troughs, which are the sites of spreading and are approximately perpendicular to the faults.

Estimated sedimentation rates within the gulf are high, especially in the northern part. This area received large volumes of sediment from the Colorado River before the 20th century. The thick cover of sediments that blankets the floor of the gulf obscures many of the features associated with both rifting and transform faulting; however, data from geophysical surveys

and sea-floor drilling throughout the gulf have contributed to unraveling its history. In the Guaymas basin near the middle of the gulf, for example, accumulation rates for the late Pleistocene and Holocene (2 m.y. ago to the present) may exceed 2 meters per 1,000 years in some areas (Curray and others, 1982). Bathymetry (the measurement of ocean depth and topography) and geophysical magnetic and seismic data reveal the presence of three active transform faults separated by two narrow troughs in the Guaymas basin (Bischoff and Henyey, 1974). The troughs are sites of active spreading, where an estimated 5 to 6 centimeters of new crust are added each year (Larson and others, 1972; Moore and Curray, 1982).

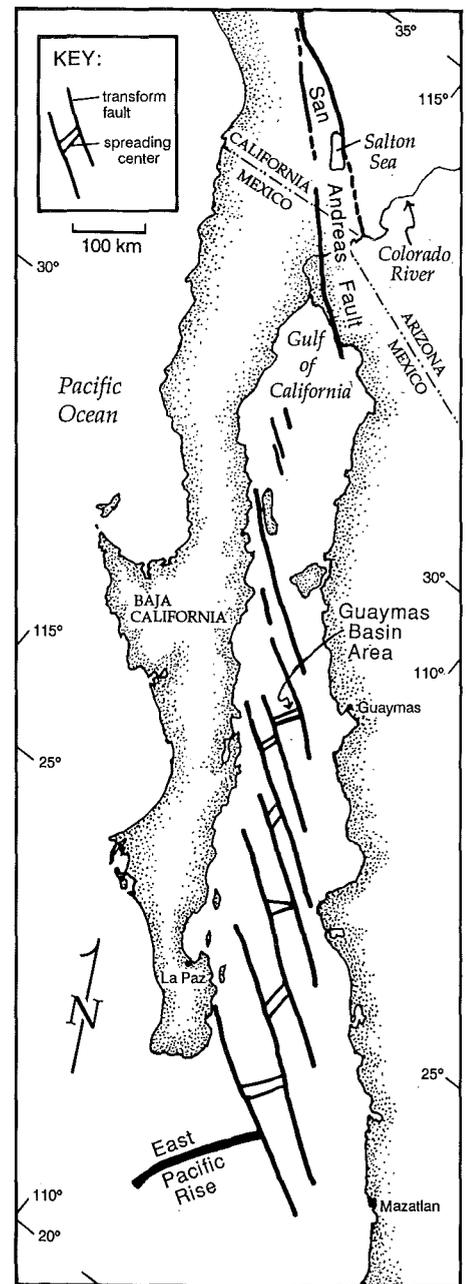


Figure 5. Transform faults and spreading centers in the Gulf of California. Note: Faults associated with the San Andreas fault system are shown in greater detail than in Figure 2. Modified from Moore, 1973, p. 1886.

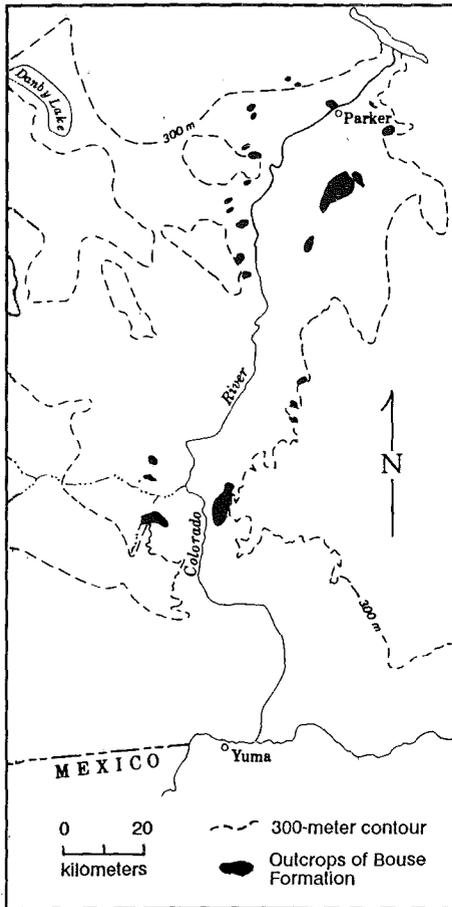


Figure 6. Distribution of the Bouse Formation. From Smith, 1970, p. 1418.

### The Salton Trough and Colorado River

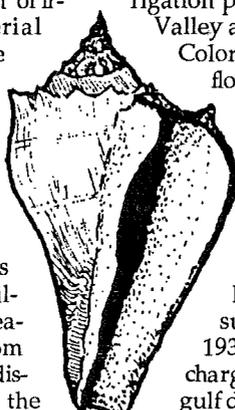
At its northern end, the Gulf of California spreading system is linked with the Salton Trough and the San Andreas fault system (Figure 5). The Salton Trough is a structural continuation of the Gulf of California that has been cut off from the gulf by sediments deposited by the Colorado River. It includes the Colorado River delta and the Mexicali, Imperial, and Coachella Valleys. In some areas, the floor of the trough lies more than 402 meters below sea level (Brusca, 1980). The northern gulf and proto-gulf once extended into the trough, forming a large embayment at various times during the late Miocene and early Pliocene, approximately 11 to 3 m.y. ago (Metzger, 1968).

Although geologists dispute when and where the Colorado River began flowing into the gulf, evidence suggests that the local drainage system that developed at the northern end of the gulf eventually joined the Colorado River during the late Miocene to early Pliocene (5.5 m.y. ago; Lucchitta, 1972, 1989). The absence of older deposits associated with a south-draining river system in southwestern Arizona and the presence of basin sediments deposited by interior drainages support this scenario (Eberly and Stanley, 1978). The depositional condi-

tions of the Bouse Formation, which consists of Miocene-Pliocene estuarine deposits exposed along the Colorado River from Yuma to north of Parker (Figure 6), become progressively less salty to the north (Metzger, 1968; Smith, 1970). This requires an influx of fresh water during deposition of the Bouse Formation, which suggests that the ancestral Colorado River had begun to drain into the Bouse embayment and, ultimately, the Gulf of California (Lucchitta, 1972, 1989).

The Colorado River progressively filled the estuary with sediments until its delta reached the Salton Trough. The Imperial Formation (Miocene-Pliocene age) of the Salton Trough area contains a well-defined horizon, above which are fossils in rocks that were derived from the Colorado Plateau. These fossils record the integration of the northern Colorado River with the southern drainages in the Salton Trough area (Lucchitta, 1972, 1989). The delta deposits of the Colorado River eventually extended the entire width of the northern gulf, isolating the Salton Trough from the gulf. (Without the Colorado River delta, the gulf today would extend northward to approximately Palm Springs.) The river alternated its flow between the isolated trough, which became a lake, and the northern gulf, but currently flows only into the gulf. The lake dried up and remained dry until 1905, when floods destroyed the headworks of an irrigation canal and diverted the Colorado River into the fertile Imperial Valley. For 2 years, the entire river flowed down the canal and emptied into the trough. The canal was repaired in 1907, leaving behind the no-outlet Salton Sea (Reisner, 1986).

Human activities have also affected the Colorado River delta and the Gulf of California. Before the 20th century, sediments carried by the river made their way as far south as La Paz, approximately 1,000 kilometers from the river's mouth. With the construction of irrigation projects in the Imperial Valley and dams along the Colorado River, river flow into the gulf has been reduced to zero (Brusca, 1980). The average annual flow from 1934 to 1935 was more than 15 million acre-feet, as measured near Yuma. From 1935 to 1964, the annual discharge of river water into the gulf decreased to slightly more than 4 million acre-feet, and by the late 1960's only subsurface percolation and diverted flows reached the gulf. Colorado River water that does flow into the gulf is typically very saline and polluted by pesticides and fertilizers (Brusca, 1980). Both sedimentation and input of fresh water, therefore, have been



dramatically decreased by human activities. In the future, the geologic history of the Gulf of California will be affected not only by natural processes but also by human intervention.

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# The Nonfuel Mineral Industry: 1989 Summary, With Focus on the Southwest

by Michael N. Greeley  
U.S. Bureau of Mines

In 1989, the value of nonfuel mineral production continued to rise in the Southwest. Preliminary figures show that the total value of production in this region exceeded one-third of the total production in the United States. Mines in the six southwestern states of Arizona, California, Colorado, Nevada, New Mexico, and Utah produced almost \$11-billion worth of mineral products, compared to the national production total of \$32 billion (Figure 1; Table 1).

Measured in dollars, the mineral output in the Southwest increased more than 10 percent over that of 1988. Mineral producers in Arizona accounted for more than 10 percent of U.S. nonfuel mineral wealth in 1989, the largest State share of production in the Nation, followed closely by output in

national statistics on 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, Cochran Mill Rd., P.O. Box 18070, Pittsburgh, PA 15236. Final production figures for 1989 are expected to be available in August.

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: Fred V. Carrillo, 1605 Evans Ave., Reno, NV 89512 (California and Nevada); Michael N. Greeley, 201 E. 7th St., Tucson, AZ 85705 (Arizona, New Mexico, and Utah); and Jane P. Ohl, Bldg. 20, Denver Federal Center, Denver, CO 80225 (Colorado).

pound, and U.S. copper-mine production increased about 5 percent during 1989. In February an agreement was reached on the terms for an International Copper Study Group, which was conceived more than 2 years ago by the United States.

Domestic gold mines continued to produce at record levels during 1989; activity was centered in Nevada, California, and Montana. Gold exploration declined slightly from the previous year, but continued to outpace exploration for other commodities, both domestically and internationally. Weakening prices throughout the year apparently reflected an easing of world political tensions and expectation of increasing inflation. Gold price declines also contributed to the closure of marginal gold-mining operations.

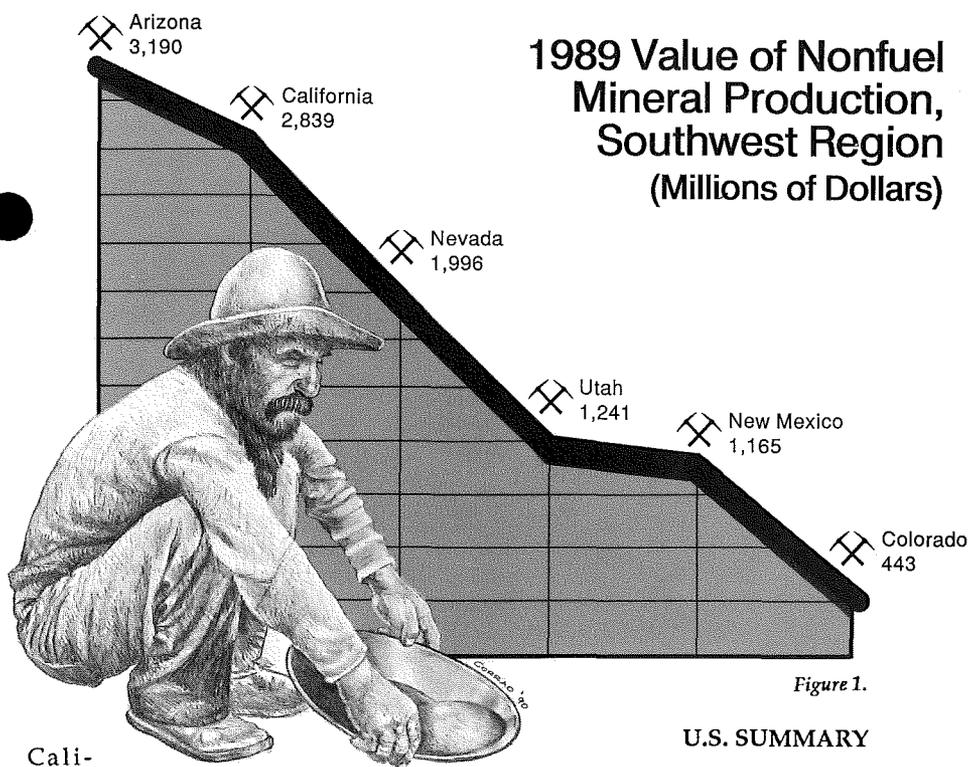
Domestic silver production increased for the third consecutive year, despite a drop in the average silver price, because of the opening of several new mines that recover silver as a byproduct. Notable among the new mines is Greens Creek, a large zinc-silver-lead mine in Alaska, which at full capacity is expected to be one of the largest domestic silver-producing mines. As in recent years, most of the new mines that opened in 1989 are gold mines where heap leaching is used to recover precious metals from low-grade ores.

A continuing, tight supply-demand situation resulted in record-high zinc prices and the opening of six zinc-producing mines in the United States. Domestic mine production rose for the third straight year; domestic smelters operated near capacity in 1989, producing the most metal since 1981. U.S. production could double in 1990, largely because of rising output at the Red Dog mine in Alaska.

World demand for lead, at about 6 million metric tons, was a record high. This resulted in the highest average price on the London Metal Exchange since 1981 and the highest average domestic price since 1980. Production increased considerably because of new zinc-silver-lead mines in Alaska and Montana and a reopened mine in Idaho. Much of this production was exported because of limited smelter capacity. The United States was expected to become a major exporter of lead concentrates, starting in 1990.

Strong overall demand diminished excess inventories of molybdenum and production increased, compared with that of 1988. Although steel demand for molybdenum weakened slightly, prices were stable because the market remained in balance. One domestic producer reopened its primary molybdenum mine in Questa, New Mexico.

## 1989 Value of Nonfuel Mineral Production, Southwest Region (Millions of Dollars)



### U.S. SUMMARY

The estimated value of nonfuel mineral production in the United States increased about 6 percent in 1989 over that of the previous year. Metal production, representing about 37 percent of the total value, rose 14 percent from \$10.2 billion in 1988 to \$11.6 billion in 1989. Although the value of industrial minerals, at \$20.2 billion, accounted for 63 percent of the 1989 total, the increase over that of 1988 was less than 2 percent.

Limited supply and low inventories maintained the copper price above \$1 per

California and Nevada (Figure 2).

These preliminary statistics were published by the U.S. Bureau of Mines (BOM), which has released State-by-State estimates of nonfuel mineral production for 1989. These estimates, generally based on 9 months of data, have been published in one volume: *State Mineral Summaries-1990*. This volume is designed to be a companion report to another BOM publication, *Mineral Commodity Summaries-1990*, which contains

U.S. demand for building and construction materials, such as construction aggregate, gypsum, and cement, remained strong in 1989. Cement imports declined slightly, representing about 17 percent of apparent consumption compared with 19 percent in 1988. Mexico, supplying 29 percent of the total, was the primary source of imports, followed by Canada, Japan, Spain, and Greece. Mexico was also the target of an antidumping petition, filed by producers in Arizona, Florida, New Mexico, and Texas, who alleged that Mexican cement was being sold in these areas at less than fair value. This was the second petition filed against Mexico in the last 3 years. The International Trade Commission made a preliminary determination that the cement industry in these regions was materially injured by Mexican imports.

U.S. demand for construction aggregate improved for the fourth consecutive year and was at a near-record level. The U.S. gypsum industry performed well, even though new housing starts decreased for the third year in a row. Increased U.S. exports of gypsum wallboard and strength in the remodeling markets offset the impact of declining housing starts.

Potash producer's stocks, which had been built up during the winter of 1988-89 in anticipation of a strong spring demand, finished the year slightly down because of a strong fall demand and extended maintenance shutdowns at mines that restricted output. At the beginning of the year, the Utah sulfate of potash facility, which was flooded by the Great Salt Lake in 1984, started operations with salts harvested from the ponds during the fall of 1988.

The U.S. salt industry was the largest producer of salt in the world. Although output was relatively unchanged compared with that of the previous year, the structure of the industry changed with mergers and acquisitions.

## STATE SUMMARIES

### Arizona

Arizona mines led the Nation during 1989 in the production of nonfuel minerals.

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 1989 are preliminary estimates.

State	Value (thousands of dollars)		Percent of Total		Principal Minerals
	1988	1989	Value in 1989 Southwest	U.S.	
Arizona	2,773,411	3,190,266	29.3	10.0	copper, molybdenum, sand & gravel
California	2,708,768	2,839,141	26.1	8.9	sand & gravel, cement, boron
Colorado	364,005	442,911	4.1	1.4	molybdenum, sand & gravel, cement
Nevada	1,944,566	1,996,062	18.4	6.3	gold, silver, sand & gravel
New Mexico	1,022,672	1,164,882	10.7	3.7	copper, potash, sand & gravel
Utah	1,014,847	1,241,484	11.4	3.9	copper, gold, magnesium metal
SOUTHWEST	9,828,269	10,874,746	100.0	34.2	
U.S. TOTAL	30,021,452	31,810,960	--	100.0	

Preliminary figures indicate that the value of output in the State totaled about \$3.2 billion, an increase of 15 percent over that of 1988 (Table 2). Supporting the first-place position was the high value (\$2.9 billion) of metallic minerals mined in Arizona. This amount represented a quarter of the value of all metals produced in the United States. Copper and molybdenum production was the highest of any State. Arizona was also among the leading States in the production of bentonite, cement, gem stones, lime, construction sand and gravel, and silver. The State's rank in domestic production of gold, however, dropped from 8th to 10th place.

Arizona mines produced approximately 60 percent of the Nation's copper in 1989. Production reflected a 5-percent increase over the 1988 level, with a 15-percent increase in value. The producer copper price rose from a 1988 average of \$1.21 per pound to \$1.31 in 1989. In general, major copper producers in the State focused their attention on expanding present operations and increasing the percentage of production achieved through the solvent extraction-electrowinning (SX-EW) process. Some companies produced more than 25 percent of their copper in SX-EW plants.

A coalition of public and private interests continued an in-situ, copper-mining research project near Casa Grande in Pinal County. The site was drilled to obtain mineralized samples and fracture-orientation data from the buried Santa Cruz oxide copper deposit. By yearend, five deep drill holes were completed. Plans were made to equip these holes for injection and recovery of solutions and to test the deposit for permeability characteristics.

Gold production decreased 37 percent in 1989. The decrease was primarily due to a drop in gold prices and to a cessation or reduction of mining operations at several gold properties in the State. Silver production, which remained constant, was chiefly recovered from copper ores or smelter flux ores. Arizona mines continued to increase their output of molybdenum. Production in 1989 was nearly half of the Nation's domestic supply.

Exploration in Arizona continued to be concentrated on the search for precious



Figure 2. T S Ary (center), Director of the U.S. Bureau of Mines (BOM), recently visited the Arizona Geological Survey to discuss nonfuel mineral production and metallic mineral districts in Arizona. With him are Michael N. Greeley (right), BOM State Mineral Officer for Arizona, New Mexico, and Utah, and Larry D. Fellows (left), Director of the Arizona Geological Survey.

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 1989 are preliminary estimates.

Mineral	Value (thousands of dollars)	
	1988	1989
Clays	1,590	2,010
Copper	2,246,093	2,592,723
Diatomite	1,208	1,208
Gem stones	3,300	3,300
Gold	64,106	35,264
Lime	29,637	W
Sand and gravel		
Construction	123,854	133,500
Industrial	3,045	W
Silver	31,974	27,236
Stone		
Crushed	33,000*	26,200
Dimension	1*	1
Other**	235,596	368,824
TOTAL	2,773,411	3,190,266

W Withheld to avoid disclosing company proprietary data; value included in "Other" figure.  
\* Estimated.  
\*\* Combined value of cement, lead (1988), molybdenum, perlite (1988-89), pyrites, salt, tin (1988-89), and values indicated by symbol W.

metals and low-cost leachable copper. Gold discoveries were announced at the Mexican Hat property in Cochise County and near Yarnell in Yavapai County. Although no new deposits of leachable copper were reported during 1989, several properties, including the Cochise in Cochise County and Sanchez in Graham County, were extensively evaluated for possible development.

The value of industrial mineral production was about \$290 million. Arizona ranked sixth in the Nation in production of construction sand and gravel, which remained the largest component of the State's industrial mineral output. Cement, lime, and crushed stone were also major contributors. In addition, Arizona mines held their position nationally among the leading producers of bentonite and naturally occurring gem stones.

The U.S. Supreme Court issued a ruling in May in a case involving royalties paid by mining companies for minerals extracted from State trust lands. The Court said Arizona must establish a method of assessing the "true value" of the minerals removed. The State will now require mining companies to pay a minimum royalty of 2 percent of the gross value of the mineral removed from trust lands, with possible increases in the future.

### California

California was the second leading State in the Nation in the production of nonfuel minerals during 1989. The value of commodities produced was estimated to be \$2.8 billion, a 5-percent increase over that of 1988. California led all States in the production of asbestos, boron minerals, portland cement, diatomite, calcined gypsum, rare-earth concentrates, construction sand and gravel, and tungsten. It was second in the production of natural calcium chloride, feldspar, gold, byproduct gypsum, magnesium compounds from seawater and brines, and sodium compounds.

Gold exploration in California continued, although at a slower pace than the previous year as lower prices and new regulations dampened enthusiasm for precious-metal exploration. Nearby residents, environmentalists, and no-growth proponents continued to impede mining operations throughout the State as they opposed the issue of new mining permits by local governments to sand-and-gravel quarries and gold-mining facilities. Operations were shut down at several gold mines during the year.

New gold-mining operations, however, at the American Girl Canyon project were approved and construction began early in the year at the mine in Imperial County. In March production began at the Royal Mountain King gold mine in Calaveras County and development was initiated at the Hayden Hill mine in Lassen County.

One cement company and the Port of Richmond discussed the possible development of an \$11-million bulk-cement distribution facility north of the Port's container terminal. The facility would use a high-capacity pneumatic unloading system and an underground piping network to remove cement from incoming ships and transport it to silos to await loading onto other ships and railcars.

The State Regional Water Quality Control Board became the sole regulator of mining wastes after passage of Assembly Bill 1413 in November. The bill reflected recommendations of a mining-waste study that the University of California at Berkeley conducted. This study endorsed eliminating dual permits and shifting regulatory authority for mining-waste matters from the Department of Health Services to the Water Board.

### Colorado

The estimated value of nonfuel minerals produced in Colorado in 1989 was \$443 million, compared with \$364 million in 1988. This 22-percent rise was mainly due to unit-price increases for molybdenum, construction sand and gravel, and zinc and a substantial production increase for molybdenum. The State ranked 23d in the Nation in nonfuel mineral production and accounted for 1.4 percent of the total U.S. value.

Colorado ranked 11th among 25 metal-producing States, accounting for slightly more than 2 percent of the Nation's total metals value. Molybdenum ranked first in Colorado in value, followed by sand and gravel, portland cement, crushed stone, gold, zinc, and other metals and industrial minerals.

Metallic mineral exploration and some mine development continued in the State, particularly in Boulder, Clear Creek, Custer, Gilpin, and Ouray Counties. Molybdenum mining and milling operations were on the upswing, principally because of the rise in price of molybdenic oxide to \$3.80 per pound in 1989, from \$3.44 in 1988. Output of molybdenum in concentrate rose to about 36 million pounds annually, up from about 30 million pounds in 1988. At the end of December, however, plans were announced to cut production at the Henderson mine by 15 percent, beginning the first week in January 1990. The cut is due to lower marketplace demand.

The total gold output in the State plummeted 48 percent. The London mine in Park County was closed in June after being in production for slightly more than a year. The Summitville surface mine was also closed in June when a crack was discovered in the embankment of the leach pad. Because of a citizens' lawsuit, mining plans were delayed at the San Luis gold project in Costilla County.

Zinc production in Colorado was estimated to be the same as in 1988, but total value increased nearly 37 percent as the average price of zinc rose to 81¢ per pound. Output of copper, lead, and silver, however, decreased considerably during the year.

Portland-cement output in Colorado was up about 9 percent; total value increased an estimated \$4.6 million to \$53.5 million in 1989. Estimated crushed-stone production for 1989 fell to 8.4 million short tons from 10.6 million in 1988. More than half of the crushed-stone output was granite; one-third was crushed limestone.

### Nevada

Nevada's 1989 nonfuel mineral production was estimated to be valued at \$2 billion, an increase of \$52 million from 1988. An almost 21-percent rise in gold production to an estimated 138.1 million kilograms (4.4 million troy ounces) accounted for most of the increase. Silver production dropped

24 percent to 463 metric tons. Nevada was the leading State in the Nation in the production of gold, silver, and barite; second in the production of diatomite, fluorspar, and lithium; and the sole producer of mined magnesite and mercury. Nevada ranked third among the States in the total value of nonfuel mineral production.

The search for precious metals continued to dominate Nevada mineral exploration. Drilling and exploration projects were reported throughout the State, particularly in Elko, Esmeralda, Eureka, Humboldt, Mineral, Nye, and White Pine Counties. Important new discoveries were reported in the Roberts Mountain area of Eureka County and in the Carlin Trend. At least 11 mining companies continued exploration efforts in Eureka County. In Humboldt County, additional exploration was conducted at the Gatchell property and several companies explored the area surrounding the Marigold mine. Exploration in Nye County included drilling at the Mother Lode project near Beatty and in the Toiyabe Mountains and investigating the west side of the Monitor Range and the Toiyabe National Forest. Exploration was also conducted near Silver Peak in Esmeralda County and at the Wind River mine in Washoe County.

Gold production continued to increase, despite a drop in the average annual price from \$439 per ounce in 1988 to about \$389 per ounce in 1989. Major expansions were underway or completed at six gold mines and at operations in the Carlin Trend. Five new mines opened during the year, one of which includes a \$27-million bio-oxidation mill that uses soil bacteria to handle refractory sulfide ore. Mine construction began at two additional properties.

The Nevada legislature concluded its longest biannual session in history with changes in Nevada's tax laws on mining profits and the first mine land-reclamation legislation in the State's history. Senate Joint Resolution 22, passed by both the legislature and a vote of the people, changed the net proceeds of mine tax from 2 percent to 5 percent. Additional proposed mining severance taxes were defeated. Assembly Bill 958, which placed responsibility for administering a new reclamation program in the Nevada State Department of Environmental Protection, was passed in the closing days of the session.

### New Mexico

The value of nonfuel mineral production in New Mexico reached an estimated \$1.2 billion in 1989, a 14-percent increase over that of 1988 and a record for the State. Mine output placed New Mexico 10th among all States in nonfuel mineral production. Most of the increase was due to the rise in output from New Mexico's metal mines, especially those that produced copper, molybdenum, and zinc. The metals sector contributed

more than \$800 million, or 71 percent of the total value of nonfuel minerals produced in the State. Metal production in New Mexico ranked fifth nationally.

Copper production remained relatively constant, showing only a modest increase in 1989. The total mine output, however, sustained the State's position as the second leading source of primary copper in the Nation.

The life of the Tyrone open-pit mine will be extended through 1991. Strong copper prices will allow the company to mine a lower-grade ore body. Operation of the SX-EW facility, however, is expected to continue for 15 years. The Tyrone mine was the third largest producer of copper in the country in 1989; the Chino mine was the fourth largest.

A large deposit of yttrium and zirconium was discovered on the Mescalero Apache Indian Reservation in Otero County. Reserves were estimated to be 2.7 million short tons containing 0.18 percent yttrium oxide and 1.2 percent zirconium oxide. When it begins producing, the deposit will be the first primary source of yttrium in the United States.

The value of industrial mineral production in 1989 was estimated at \$336 million. Potash production led all nonmetallic output by a large margin. Underground mines were responsible for more than 88 percent of potash production in the Nation. Output value increased 17 percent over that of 1988 and represented more than one-fifth of the total nonfuel mineral production in the State. Six mining and processing facilities in the Carlsbad area maintained operations

throughout the year.

In November, the U.S. Bureau of Land Management signed an order extending the royalty rate on all Federal potassium leases in New Mexico. About 85 percent of the total potash mined in the State has been on Federal leases. The royalty rate for the next 2 years will continue to be 2 percent of the gross value of output at the point of shipment.

Perlite, construction sand and gravel, and crushed stone were also major contributors to the total value of industrial minerals. The production of perlite was the largest in the Nation and pumice output was second.

The 1989 State legislature enacted Senate bill 303, designating the director of the New Mexico Bureau of Mines and Mineral Resources as the State Geologist. House bill 526 gave the Mining and Minerals Division of the New Mexico Energy, Minerals, and Natural Resources Department authority over mine registration, annual reporting, and safeguarding of surface-mine openings. The bill also limited the duties of the State Mine Inspector to mine-safety training and the enforcement of laws governing certain underground operations. Jurisdiction of the Inspector's office was transferred to the New Mexico Institute of Mining and Technology.

#### Utah

The value of nonfuel mineral production increased 22 percent to more than \$1.2 billion, a record for Utah. Mine output placed Utah eighth among all States in nonfuel

mineral production. Most of the increase was due to the strong rise in metal output, especially copper, gold, magnesium, molybdenum, and silver. The metals sector contributed more than \$1 billion, or 83 percent, of the total value of nonfuel mineral production and ranked Utah fourth nationally in metal production.

The search for nonfuel minerals was mostly concentrated on precious-metal deposits. Exploration activity was brisk for gold and silver in the mining districts of the Tintic area south of Salt Lake City and for additional reserves of gallium and germanium near the Apex mine in southwestern Utah.

Dedicated in late 1988, the modernized facility at the Bingham Canyon mine substantially increased production of copper and byproduct metals during 1989. The mine was the second largest producer of copper in the Nation. The Bingham Canyon operation maintained its role as the only producer of copper and molybdenum in Utah and as the State's largest producer of gold and silver.

North of Bingham, development was completed at the Barney's Canyon gold mine. The surface-mine and heap-leaching operation produced its first gold in late September. Production is expected to continue for 10 years at an average annual rate of 2,500 kilograms (80,000 troy ounces).

The Goldstrike mine in Washington County also began producing in 1989. Annual production from this open-pit heap-leaching operation is expected to be 1,250 kilograms (40,000 troy ounces) of gold and a similar quantity of silver; the lifespan of the mine is estimated to be 5 years.

Management announced a \$400-million modernization program for the integrated steel facility near Orem, which will require 3 to 5 years to complete. In October, steel production at the facility was reduced by 25 percent because of a nationwide decline in demand.

Utah continued to lead the Nation as the principal domestic source of beryllium. Production and sales were down slightly during the year, however, because of reduced demand in the defense, computer, and semiconductor markets. Although mine production of vanadium in southeastern Utah surged briefly in response to a temporary price increase, total output for 1989 declined from previous years. Magnesium metal production at Rowley rose after a new evaporation and precipitation pond system was completed in 1988.

The value of industrial mineral production in Utah in 1989 was about \$211 million. Portland cement, followed closely by construction sand and gravel and salt, was the largest component of the output. Lime, phosphate, potash, and crushed stone were other important contributors. Utah was one of the few States with mines that supplied magnesium compounds and sodium sulfate during 1989.

### AZGS Staff at Forefront of GSA Meeting

The 86th annual meeting of the Cordilleran Section of the Geological Society of America (GSA) was held in Tucson, Arizona from March 14 to 16, 1990. Almost 900 earth scientists attended the symposia and approximately 300 participated in the field trips. Staff members of the Arizona Geological Survey (AZGS) helped to plan the meeting, produced the field-trip guidebook, led field trips and symposia, and presented original research through 13 talks.

Jon Spencer prepared budgets for 18 field trips and edited the guidebook. He also coauthored four papers, chaired the poster symposium "Geologic Maps of Metamorphic Core Complexes and Highly Extended Areas," and helped lead a field trip to examine evidence of thrusting and deformation in the Harcuvar Mountains in west-central Arizona. Phil Pearthree arranged transportation for field trips, coauthored four papers, and helped lead a field trip to examine the geomorphology of the Pitaycachi fault

in Sonora, Mexico. Steve Reynolds presided over the symposium "Mesozoic Evolution of Southwestern North America," coauthored seven papers, and helped lead the field trip to the Harcuvar Mountains. Garrett Jackson presided over the symposium "Quaternary Tectonics and Geomorphology," wrote one paper, and coauthored another. Mike Grubensky wrote one paper, and Karen Demsey and Steve Slaff coauthored two others. John Welty presented a poster session.

Pete Corrao and Evelyn VandenDolder designed the cover and final layout and supervised the printing of the field-trip guidebook. Pete, Evelyn, Sherry Garner, and Nancy Schmidt wrote and designed numerous leaflets, brochures, and displays for the meeting. Pete and Sherry also produced graphic slides for talks presented by staff geologists. Lauri Colton organized the AZGS exhibit booth, which was managed by Lauri, Evelyn, Denise Siewert, Tom McGarvin, Jane Hinkley, and Rose Ellen McDonnell.

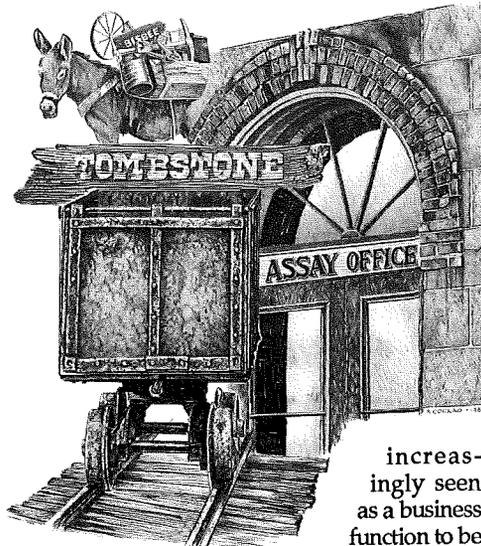
# The Future of Economic Geology in Arizona: A Perspective From Industry\*

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Changes have occurred in the exploration process, and as a result, the future isn't what it used to be. Exploration departments and budgets of mining companies are smaller. The exploration geologist in the porphyry copper decades of 1950 to 1980 was primarily a field mapper and core logger—a practical scientist. Claim staking, land work, drill management, core splitting, geochemical sampling, and drafting—often done in the past by support staff—are now routine tasks of the field geologist, which leaves less time for geologic work. Starting in the 1980's, exploration geologists have been searching for precious metal targets in which the ore mineral is nearly invisible. As a result, the geologist is less a mapper and more a designer and manager of assay quality-control and sample-collection programs. The geologist now relies on the assayer instead of the hand lens to determine if ore grades are present. Core logging is a lost art because most drilling is done by rotary methods that provide small, hard-to-log muddy chips of rock at the rate of a sample every few minutes. Many geologists under the age of 35 have never logged drill core, nor have they learned the importance of careful observation of rocks. At times it seems like exploration by remote control.

In addition to the exploration process, the nature of the participants has changed. Gold deposits are commonly small and technically simple to mine. They may be discovered by low-cost surface prospecting and shallow drilling and developed at low capital cost. This means that small exploration groups can be important players. Many of the small groups do not maintain permanent exploration offices, have no permanent exploration staff, and live in another State or country. They often operate without anyone knowing of their presence. They are numerous and move quickly; to compete, other mining companies must move quickly too. There is less time for science in this type of environment. Some managers have proposed that geologists should not spend time summarizing the results of exploration on submarginal drill projects. The next generation of explorers, if there is one, may have to repeat the work.

Corporate philosophy concerning exploration has also changed. In the past, mining companies explored because they were expected to explore. Now exploration is



increasingly seen as a business function to be evaluated on performance. In other words, if one can't find something, one may not continue to explore. The net effect is more pressure, which is good, but pressure also increases the focus on short-term results, which may not be good because it leaves less time for systematic geologic study. As a commentary on these changes, I have seen far less recording of geologic data and thought during the 1980's than during the porphyry copper boom. Mine geologists do less mapping and more grade control than before, which leaves the explorationist with a less complete database upon which new exploration models and concepts may be built. The elegant exploration research groups run by Anaconda, Kennecott, and other companies, which made significant scientific contributions to the literature, are a thing of the past. They are not cost effective because they cannot provide new concepts quickly enough to get a jump on the competition.

Most scientific research on ore deposits and exploration methods, whether gathered by industrial, academic, or government groups, is 4 to 10 years behind discovery. In other words, exploration discovery drives the science, not the reverse. Obviously, one can't study an orebody until it has been found.

Although scientific research does not often initiate major discovery cycles, it has contributed significantly to the extension of those cycles. The numerous publications on porphyry copper deposits from the University of Arizona during the 1960's and 1970's are good examples of this phenomenon. Science by academic and government groups, however, is becoming increasingly laboratory and computer oriented because that is what gets published in

peer-reviewed journals. These data are far more rapidly collected than field data and reflect a response to the pressure on researchers to publish quickly to achieve tenure and the reputation required to obtain research grants. The dependence on the laboratory is well illustrated in an *Economic Geology* article in which six coauthors from four prestigious research groups proposed an origin for a major ore deposit based on a single rock sample (Eldridge and others, 1988). As the current generation of tenured economic geology professors with careers balanced by field and laboratory work is gradually succeeded by the laboratory experts, one wonders who will teach the technique and importance of field observations to future explorationists. Maybe industry will, or maybe industry will hire structural geologists who still gather field data and teach them about ore deposits.

It is rare to find a descriptive ore deposit paper based on field work in a peer-reviewed journal. Yet, it is the field-based descriptive paper that most often contains the clues useful to explorationists. These descriptions identify the odd, single deposit types that may be the precursors of the next exploration model. Getchell and Gold Acres in Nevada, both classic Carlin-type gold deposits, were active mines 20 years before the Carlin mine was discovered and a major new deposit type finally recognized. The uranium mines at Beaverlodge in Saskatchewan and Rum Jungle in the Northern Territory of Australia were known decades before the discovery of the major unconformity-related deposits in the Athabaska Basin and Alligator River areas. Fine-grained gold occurrences in laterite were known in Western Australia 30 years before the discovery of the giant Boddington gold deposit near Perth. Descriptive field information is not being recorded in a consistent professional way in mines, during exploration, or in scientific journals because of budget reductions and short-term philosophies and because it doesn't help in winning tenure or grants. Future discovery rates will suffer as a result.

In light of these observations, what is the future of economic geology in Arizona? Based on the data on porphyry copper deposits, there will not be another surge in copper exploration at the current or expectable copper prices. The discovery rate for porphyry copper deposits fell precipitously in the 1970's because of significant

\* Editor's note: This article is based on a talk that the author, who was the invited luncheon speaker, gave at a special symposium sponsored by the Arizona Geological Society and the Arizona Section of the American Institute of Professional Geologists. At the symposium, which was held in Phoenix in November 1989, summaries of geological activities were presented by the directors of State and Federal geological and mineral resource agencies and by representatives of the geology departments in the three major universities in Arizona. Dr. Graybeal's speech is reprinted here with permission.

increases in the depth of mineralization with time. Arizona has largely been swept clean of porphyry copper deposits that are minable by open-pit techniques. Even if deep deposits could be located, the financial risk of block caving would be high.

The gold rush has largely bypassed Arizona. During the past 4 years, however, the discovery rate has substantially fallen in the traditional gold provinces of North America, even though gold prices are still at profitable levels. Geologists are now searching for greener pastures. A modest gold deposit was recently discovered at Yarnell, Arizona; coupled with apparent gold discoveries in carbonate rocks in northern Mexico and in volcanic rocks near Pearce, Arizona, this discovery may indicate a short-term increase in exploration activity in the State.

If one assumes that increased levels of exploration and economic geology activities are healthy for Arizona, the following suggestions might contribute to that health.

(1) **Publications.** The symposia proceedings and guidebooks that contain short descriptive papers published by the Arizona Geological Society must continue. These publications are important sources of descriptions of ore deposits and their environments and fill a void left by many of the more instrumentally minded research organizations and journals.

(2) **Mining Claim Records.** State and Federal agencies should keep a permanent and retrievable record of locations of all claims staked or assessed in Arizona, along with owners' names and addresses. Those engaged in small-scale exploration activities acquire potentially useful data, but often their names and data are forgotten or lost. Contrary to popular opinion, keeping exploration data confidential is not inefficient because information owned by one group is often reviewed by others under protection of confidentiality agreements. Industry does not want exploration data in public files, but does want to know who did the work. Unlimited access to exploration data would compromise the interests of shareholders of companies who paid for the data. Second or third exploration efforts by the same company on the same property have been known to result in discovery, an opportunity that would otherwise be lost. The taker of the risk is entitled to keep the data or to trade or sell it at his or her sole discretion, usually the only reward for the risk. Knowledge that work was done in an area would not compromise confidentiality, but could increase long-term exploration efficiency.

(3) **Mining District Research.** More geologic research, including mapping at intermediate scales, is needed in mining districts to enlarge the exploration target. This includes geologic maps and studies of edges of ore-forming systems. These boundaries may exceed visual limits and be defined by fluid-inclusion paleothermal anomalies or stable-isotope patterns. This need

was a nearly unanimous opinion expressed by exploration geologists in a 1981 survey by the Society of Economic Geologists and in more recent panels, but has largely been ignored. A focused study of areas of detachment faulting, such as the Copperstone mine and other smaller Arizona gold deposits, might stimulate exploration in what is conceptually a very difficult geologic environment.\* Most mapping exercises stop at the edges of orebodies, and the current CUSMAP effort by the U.S. Geological Survey is too regional in scope for direct application to exploration.

(4) **In Situ Mining.** Mining research agencies, such as the U.S. Bureau of Mines and newly formed Copper Research Center, should increase research on in situ mining of copper oxides and sulfides. The current research program by Asarco, Freeport, and the U.S. Bureau of Mines at the Santa Cruz oxide deposit near Casa Grande will evaluate environmental permitting of an in situ test and obtain information on operating costs. This project has no guarantee of success and has endured the unpredictable crises typical of any research program. Public concern about the impact of mining on the environment will increasingly influence mining development. In situ leaching offers a way to extract metal at low capital cost with no pits, collapse zones, dumps, tailings, or smelting. Aspects of in situ mining involve processes that are very similar to ore deposition and supergene enrichment; experience at Santa Cruz has shown that any research program in this field should budget for extensive geologic input.

(5) **Resource Estimates.** Mineral-resource appraisals for land-use planning are dangerous. These appraisals are based on known ore deposit models and should not be used to declare areas barren of minerals. Such appraisals are flawed because they are forced to estimate the abundance of as-yet-unknown types of ore deposits as zero. Persons who state that all ore deposit types are already known remind one of the director of the U.S. Patent Office, who suggested in 1899 that the office be closed because everything that could be invented had been invented.

(6) **Industrial Minerals.** Conventional wisdom holds that, in the industrial mineral business, one explores for markets and then looks for ore; however, 100 years of mining industrial minerals in the West, along with rapid population growth, have almost depleted some of these ores. It may be time to abandon conventional wisdom and explore for new deposits. A recent

\* Editor's note: *Geology and Mineral Resources of the Buckskin and Rawhide Mountains, West-Central Arizona*, published after Dr. Graybeal's speech was prepared, is such a study. It focuses on the geology of a Cordilleran metamorphic core complex and the mineralized areas along a detachment fault. Published by the Arizona Geological Survey as Bulletin 198, this 280-page report contains three large maps and may be purchased for \$35.50 (includes shipping charges).

workshop addressed this subject.\*

(7) **Natural Resource Education.** Formal secondary-school education in earth science, natural resources, and the environment should be required for every student in the country. I'm sure many have experienced the vignette of a dinner conversation with an eighth grader who announces, "We're poisoning our environment, and it's industry's fault," then adds wisely, "I learned it in school." Occasional lectures at schools by geologist mothers and fathers are worthwhile, as are industry-sponsored films on the importance of natural resources, but they are a needle in the haystack.

Nationwide statistics on secondary-school earth-science education are incomplete, but the American Geological Institute (AGI) in Alexandria, Virginia has compiled some data. New York requires 1 year of earth science, typically in 9th grade, as part of its Regents curricula. Montana, Idaho, and Maine offer earth science as an elective; these classes are accepted as college-preparatory laboratory-science courses. A 1985-86 National Science Teachers Association survey, however, indicated that only 30 percent of the Nation's schools offer earth science in any form. Although the AGI cautions that these data are incomplete, they do seem to indicate that high school students are earth-science illiterate, except possibly in New York. In addition, Green (1989) found that virtually all college freshmen who plan teaching careers will major in education, not in the field they will teach, which raises the question of whether future geology teachers will know enough geology to teach it.

Arizona, as a major producer of metals, consumer of water, and population growth center, should require that high school students study earth science and those teaching it have an adequate scientific background. Waiting until college is too late. Furthermore, college-level, introductory geology courses are not required of every student and miss those who never attend college. All students, however, may become voters. An understanding of natural resource issues, flood-plain locations, and earthquake zones will make students more effective voters and is no less important than knowing how to dissect a frog, calculate angular momentum, or balance a chemical equation. Education is a public function and requires leadership at the State-agency or political level; an initiative from the mining industry regarding natural resource educa-

(continued on page 12)

\* Editor's note: This workshop, held to improve public understanding of the importance of industrial minerals to Arizona's economy, was jointly sponsored by the U.S. Geological Survey (USGS) and Arizona Geological Survey. The workshop conclusions are summarized in USGS Bulletin 1905, *Arizona's Industrial Rock and Mineral Resources--Workshop Proceedings*. Copies are available for \$5.00 each from the Books and Open-File Reports Section, USGS, Federal Center, Box 25425, Denver, CO 80225.

# Theses and Dissertations, 1989

The following list includes theses and dissertations on Arizona geology, geological engineering, hydrology, and related subjects that were awarded in 1989 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 according to the codes listed below.

Arizona State University, Tempe, AZ 85287; (602) 965-9011. (Gg-Geography; G1-Geology)

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

University of Arizona, Tucson, AZ 85721; (602) 621-2211. (CE-Civil Engineering and Engineering Mechanics; G-Geosciences; MGE-Mining and Geological Engineering; MSE-Materials Science and Engineering; RNR-Renewable Natural Resources; SWS-Soil and Water Science)

## Arizona State University

- Archer, Bradford, Quaternary fossil tortoises of the Phoenix basin: M.S. thesis, 174 p. (G1)
- Doorn, P.K., Geologic and gravimetric investigations of the Carefree basin, Maricopa County, Arizona: M.S. thesis, 307 p. (G1)
- Drosendahl, J.K., Environmental geology of the Rio Salado development district, eastern part, Maricopa County, Arizona: M.S. thesis, 122 p. (G1)
- Gjoen, B.E.S., Formation of micrite and sparite from the breakdown of algae in a pedogenic environment: M.S. thesis, 92 p. (G1)
- Harrison, D.H., A structural and petrographic analysis of two large intersecting shear zones west of Prescott, Arizona: M.S. thesis, 110 p. (G1)
- Haschenburger, Judith, Variation of copper in stream sediment: M.S. thesis, 67 p. (Gg)
- Lee, S.E., The effect of Glen Canyon Dam on the Colorado River, Grand Canyon, Arizona: M.S. thesis, 108 p. (Gg)
- Matheney, R.K., Oxygen isotopic investigations in stepwise fluorination of hydrous silica and other geologic materials: Ph.D. dissertation, 136 p. (G1)

- Paul, T.A., Environmental rheology and microstructures of kyanite deformed near the sillimanite boundary: M.S. thesis, 96 p. (G1)

## Northern Arizona University

- Conway, F.M., Volcanology, geochemistry, and petrology of the west-central Mormon Mountain volcanic field, northern Arizona: M.S. thesis, 147 p. (G)
- Cook, M.J., Depositional and architectural analysis of the lower massive sandstone (Triassic Moenkopi Formation) of north-central Arizona: M.S. thesis, 141 p. (G)
- Darr, M.J., Hydrogeology of the Oak Creek area, Verde Valley, Arizona: M.S. thesis, 268 p. (G)
- Grover, P.W., Stratigraphy and depositional environment of the Surprise Canyon Formation, an Upper Mississippian carbonate-clastic estuarine deposit, Grand Canyon, Arizona: M.S. thesis, 303 p. (G)
- Harwood, R.D., Cinder cone breaching events at Strawberry and O'Neill Craters, San Francisco volcanic field, Arizona: M.S. thesis, 104 p. (G)
- Lindholm, M.S., Volcanology, petrology, and structural geology of Proterozoic metavolcanic rocks in Mescal Canyon, Jerome, Arizona: M.S. thesis, 153 p. (G)
- McCormack, D.C., The geology of Wupatki National Monument, northern Arizona: M.S. thesis, 97 p. (G)
- Sanders, C.M., Stratigraphy, sedimentology, and paleogeographic significance of the sedimentary portion of the Tertiary Hickey Formation, central Arizona: M.S. thesis, 143 p. (G)

## University of Arizona

- Ali, A.S., Reactions of urea phosphate in calcareous and alkaline soils; ammonia volatilization and effects on soil sodium and salinity: Ph.D. dissertation, 88 p. (SWS)
- Brooks, M.W., Distribution and assessment of expansive clay soils in the Tucson basin, Arizona: M.S. thesis, 150 p. (CE)
- Cai, Wenlong, Application of network flow and zero-one programming to open-pit mine design problems: Ph.D. dissertation, 225 p. (MGE)
- Evet, S.R., Field investigations of evaporation from a bare soil: Ph.D. dissertation, 426 p. (SWS)
- Fink, J.B., Induced polarization: electrochemistry, fractal geometry, and geohydrologic applications: Ph.D. dissertation, 370 p. (MGE)
- Flack, Paul, A method for establishing baseline soil loss rates on surface mine sites: M.S. thesis, 45 p. (RNR)

- Holbert, S.B., Development of a geographic information system based hydrologic model for stormwater management and landuse planning: M.L.A. thesis, 114 p. (RNR)
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## PROFESSIONAL MEETINGS

**CONSERV 90.** National water-supply conference, August 12-16, Phoenix, Ariz. Contact CONSERV 90, 6375 Riverside Dr., Dublin, OH 43017; tel: (614) 761-1711.

**Taking the Arizona Groundwater Management Act into the '90s.** Symposium, September 6-7, Casa Grande, Ariz. Contact Mary G. Wallace, Water Resources Research Center, Geology Bldg., Rm. 318, University of Arizona, Tucson, AZ 85721; tel: (602) 621-7607.

**The Colorado Plateau During the Mesozoic Era.** Symposium, September 29-30, Flagstaff, Ariz. Contact Mike Morales, Museum of Northern Arizona, Rt. 4, Box 720, Flagstaff, AZ 86001; tel: (602) 774-5211.

**National Colloquium on Professional Registration for Geologists.** Presented as part of the Association of Engineering Geologists annual meeting, October 1-5, Pittsburgh, Pa. Contact Robert E. Tepel, AEG Committee on Professional Registration, 767 Lemonwood Ct., San Jose, CA 95120.

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tion might be seen as self-serving. Perhaps the three R's will become the four R's: reading, "riting," "rithmetic," and resources.

**(8) Tax Holiday for Recapture of Capital Investment.** The least likely, but perhaps most effective, way to encourage exploration and new mine development in Arizona is to do what British Columbia did for many years: provide miners with a tax-free period, during which they could recapture their capital investment in new mine development. This policy was very effective, and any State that offered this mining incentive would almost certainly be explored more actively.

Trying to predict economic geology trends in Arizona may not be realistic. A better approach might be for Arizona geologists to decide where they want economic geology to go and then develop a strategy to get it there. Other exploration groups should be asked what would attract them to Arizona in addition to a geologic environment that is favorable for discovery. This article represents the perspective of an outsider and I hope will encourage a more broadly based discussion among members of the geologic community.

### Arizona Geology

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