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FIELDNOTES

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Volcanic History of Arizona

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Although Arizona lacks active volcanoes, it was the site of massive outpourings of lava and volcanic ash during the recent and more distant geologic past. Volcanism not only formed the oldest rocks in Arizona 1.8 billion years (b.y.) ago, but also constructed the State's highest mountains, the San Francisco Peaks, within the last 3 million years (m.y.). Volcanic rocks are widespread throughout the State and dominate much of its scenery (Figure 1). This article summarizes the volcanic history of Arizona and briefly describes the importance of volcanic rocks in the State.

***Figure 1.** Aerial photograph of S P Crater and basalt flow in the San Francisco volcanic field, north of Flagstaff. The eruption that formed this cinder cone and lava flow occurred relatively recently, about 70,000 years ago. Photo by David D. Nations.*

Volcanic Episodes

Six major episodes of volcanism are represented within the geologic record of Arizona. These episodes locally, but unequally, affected all three of Arizona's geologic-physiographic provinces: Colorado Plateau, Transition Zone, and Basin and Range Province (Peirce, 1984). Volcanic activity within the last 10 m.y., for example, was intense along the boundary between the Colorado Plateau and Transition Zone, but was less common in other parts of the State. Because each volcanic episode was localized, mineral and energy resources related to volcanism are also unequally distributed. This unequal distribution has, in turn, dramatically affected the settlement of Arizona and continues to exert some influence on the population distribution.

The earliest volcanic episode in Arizona occurred during the Precambrian Era between 1.8 and 1.6 b.y. ago and formed much of the continental crust that underlies the region today. Volcanic rocks formed during this time are most widely exposed in the Transition Zone and parts of the Basin and Range Province (Figure 2). Volcanism probably began when the oceanic crust was pulled apart, creating a rift in the sea floor from which basalt was erupted. This process of sea-floor spreading is occurring today along the mid-oceanic ridges circling the Earth. Large volcanic islands, some similar to Hawaii and others similar to the Aleutian Islands in Alaska, were built upon the basaltic sea floor. The central volcanoes erupted basalt and more silica-rich lavas and were surrounded by aprons of sedimentary debris derived from explosive eruptions of volcanic ash and from erosion of the volcanoes. Heat from the central volcanic conduits caused water to circulate within and around the volcanoes, which led to deposition of mineral deposits such as the famous copper-silver-gold ores of Jerome. Collisions between converging volcanic arcs deformed and metamorphosed the volcanic and associated sedimentary rocks, locally converting them into schist (Anderson, 1986). During and after these collisions, large masses of granitic magma intruded into and helped stabilize the continental crust of the region.

A second episode of Precambrian volcanism occurred about 1.1 to 1.2 b.y. ago, but was more areally restricted and less voluminous than the previous episode. This volcanism is evident in basalt flows and rhyolite tuffs (compacted volcanic ash) interbedded with sedimentary rocks of the late Precambrian Apache Group near Globe and the Unkar Group of the Grand Canyon (Figure 2). These rocks accumulated in basins within the stable continental interior and were later injected with horizontal sheetlike intrusions, or sills, of diabase, a dark-colored igneous rock that forms by crystallization of basaltic magma at depth. These diabase sills are well displayed in the walls of the Salt River Canyon northeast of Globe. The presence of basalt flows, tuff, and diabase sills within a continental basin suggests that volcanism and sedimentation accompanied a period of minor continental rifting.

After this second episode, volcanism was evidently absent in Arizona for almost 1 b.y., or more than half of the State's entire geologic history. During this prolonged volcanic quiescence, which includes all of the Paleozoic Era (570 to 245 m.y. ago), Arizona was a relatively stable, topographically subdued region that was intermittently flooded by shallow seas. This interval of relative stability was interrupted in the early Mesozoic, when volcanic ash and detritus were blown by winds and washed by streams into northern Arizona from distant volcanoes to the south and west, probably in northern Mexico or southern California (Peirce, 1986). The volcanic ash and debris were deposited in the Upper Triassic Chinle Formation and became altered to impart the variegated colors of the Painted Desert and Petrified Forest. By Jurassic time (190 m.y. ago), volcanism became widespread in a northwest-trending volcanic belt that crossed southern Arizona from Douglas to Parker (Figure 3). Volcanoes within this belt erupted regionally extensive rhyolitic tuffs and more localized rhyolitic lavas. The volcanic landscape was locally overrun by sand dunes, believed to have migrated southward from the great deserts that existed during deposition of the Lower Jurassic Navajo Sandstone of the Colorado Plateau. The resulting interbedded Jurassic volcanic rocks and sandstones are present in the Santa Rita and Baboquivari Mountains of southern Arizona and in several mountain ranges near Parker.

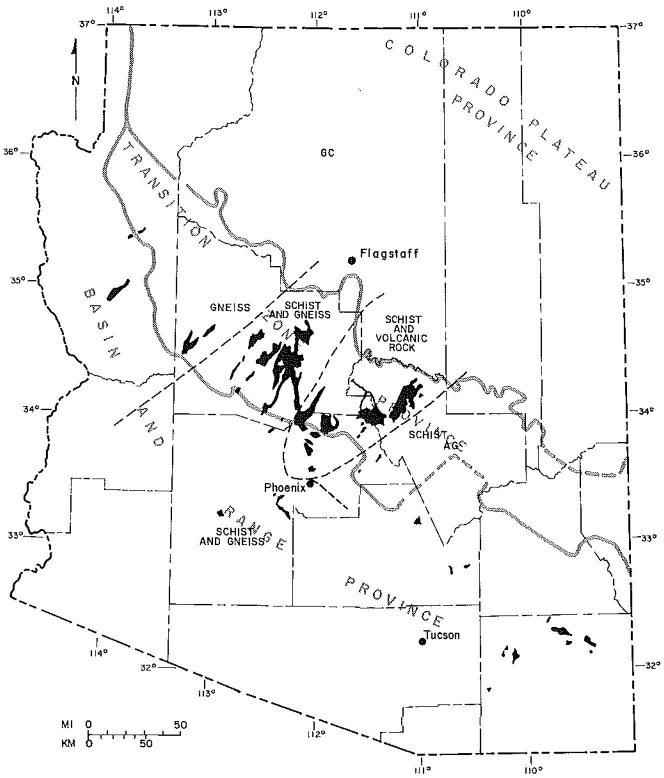


Figure 2. Outcrops of Precambrian and metamorphosed volcanic rocks formed during the first volcanic episode (1.6-1.8 b.y. ago) are shown in black. Deformation and metamorphism under high temperatures and pressures have generally converted these volcanic rocks into schist or gneiss. Outcrops of rocks formed during the second episode (1.1-1.2 b.y. ago) are too small to show individually, but occur in the Unkar Group in the Grand Canyon area (GC) and in the Apache Group near Globe (AG).

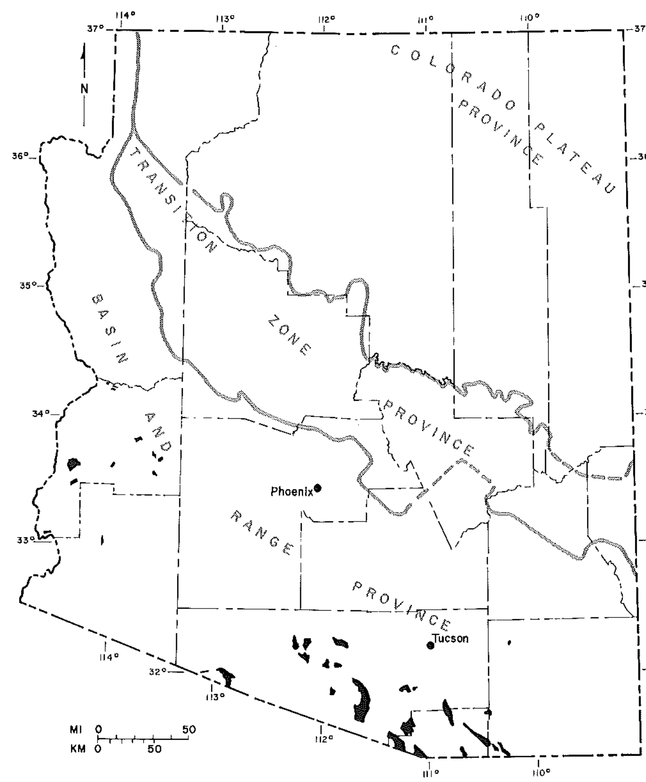


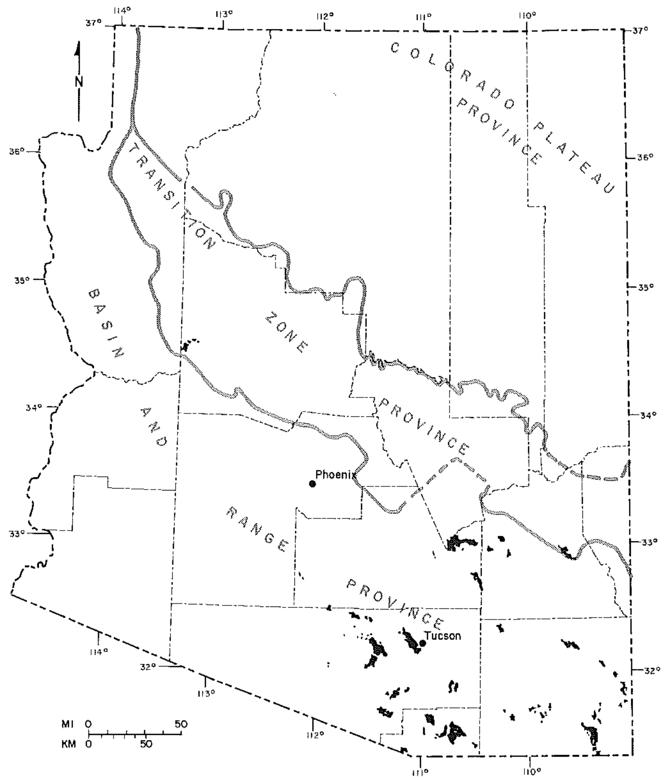
Figure 3. Outcrops of Jurassic volcanic rocks occur in a northwest-trending belt across southern Arizona.

In Late Jurassic time (145 m.y. ago), volcanism moved westward out of Arizona and into coastal California and Baja California, where a volcanic arc formed along the continental margin, much like the present-day Andes of South America. This volcanism occurred above an east-dipping subduction zone, where a plate of oceanic crust in the Pacific Ocean descended into the mantle beneath coastal California and Mexico. Volcanism continued along the coast during most of the Cretaceous, whereas southern Arizona was largely free of volcanoes and was locally inundated by shallow seas from the east.

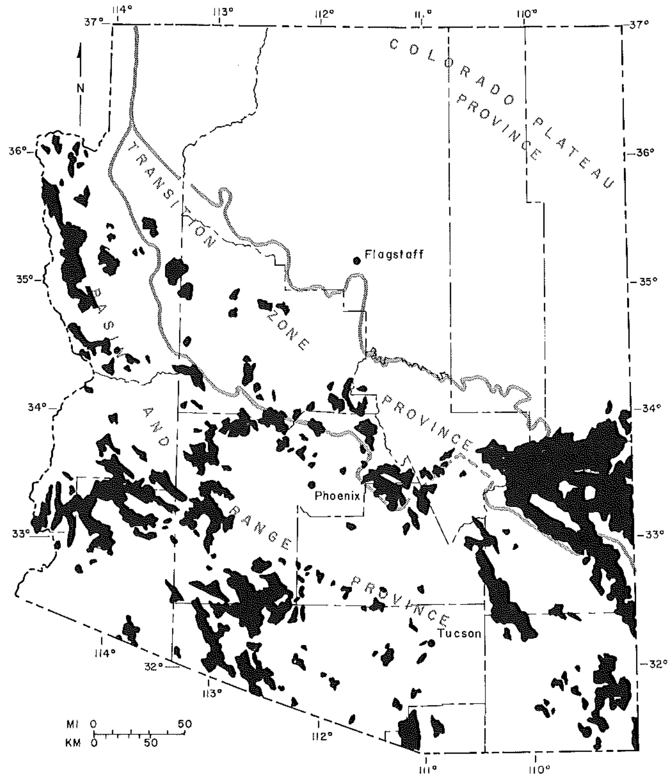
Arizona's fourth volcanic episode occurred during Late Cretaceous to early Tertiary time (85 to 45 m.y. ago), when volcanism and associated igneous activity migrated eastward back into Arizona and adjacent New Mexico. This eastward sweep of magmatism was due to a decrease in the dip or angle of the subducted oceanic plate beneath the region (Coney and Reynolds, 1977). Volcanic rocks of this age are most widely preserved in southeastern Arizona (Figure 4), but originally covered parts of western Arizona, where they have been removed by erosion. This volcanic episode included construction of andesitic stratovolcanoes, as well as catastrophic caldera collapse that accompanied eruption of large volumes of volcanic ash. Caldera collapse locally resulted in the deposition of breccias that contain house-sized blocks of limestone, granite, and other rocks derived from the walls or deeper levels of the caldera. Remnants of such calderas are probably present in the Silver Bell, Tucson, and Santa Rita Mountains near Tucson (Lipman and Sawyer, 1985). During this episode of volcanism, large porphyry copper deposits formed in the cooling magma chambers underneath the volcanoes. These copper deposits, like the associated volcanic rocks, are most common in southeastern Arizona, where they escaped complete removal by erosion. Volcanism was followed by widespread melting of the lower continental crust, which formed large granitic masses in the Santa Catalina Mountains, Baboquivari Mountains, and southwestern Arizona.

There was a pronounced lull in volcanic activity during the early Tertiary from 50 to 35 m.y. ago (Shafiqullah and others, 1980). This interval was followed by a middle Tertiary episode of intense volcanism that covered much of the Basin and Range Province with regional ash-flow tuffs and more areally restricted rhyolite, andesite, and basalt flows. During this episode, a single catastrophic eruption west of Kingman deposited a layer of ash-flow tuff over an area of 35,000 km^2 between Peach Springs, Arizona and Barstow, California (Glazner and others, 1986). Volcanism swept westward across Arizona between 35 and 15 m.y. ago, as the dip of the subducted oceanic plate decreased beneath Arizona (Coney and Reynolds, 1977). As a result, middle Tertiary volcanic rocks are mostly 25 to 35 m.y. old in southeastern Arizona, but 15 to 25 m.y. old in western Arizona. These middle Tertiary volcanic rocks are widespread throughout the Basin and Range Province (Figure 5) and provide the backdrop for some of the region's most scenic areas, including the Chiricahua, Galiuro, Superstition, and Hieroglyphic Mountains, Picacho Peak, the Kofa National Wildlife Refuge, Organ Pipe National Monument, and Apache Leap near Superior. Middle Tertiary volcanic rocks are present, but much less common, in the Transition Zone and Colorado Plateau. Middle Tertiary volcanism was locally accompanied by deposition of precious- and base-metal veins from hot fluids that circulated near the volcanic centers and along major fault zones.

The sixth and last major episode of volcanism in Arizona occurred during the late Cenozoic since 15 m.y. ago. It coincided with faulting that formed many of the deep basins in the Basin and Range Province and Transition Zone. In contrast to the previous episode, volcanism largely consisted of basalt flows that are most widely exposed in the Transition Zone and along the southwestern edge of the Colorado Plateau (Figure 6). The basaltic volcanism on the Colorado Plateau was locally accompanied by more silica-rich flows that built the extinct and



DISTRIBUTION OF
LARAMIDE (80-50 m.y.) VOLCANIC ROCKS



DISTRIBUTION OF MID-TERTIARY (40-15 m.y.) VOLCANIC ROCKS

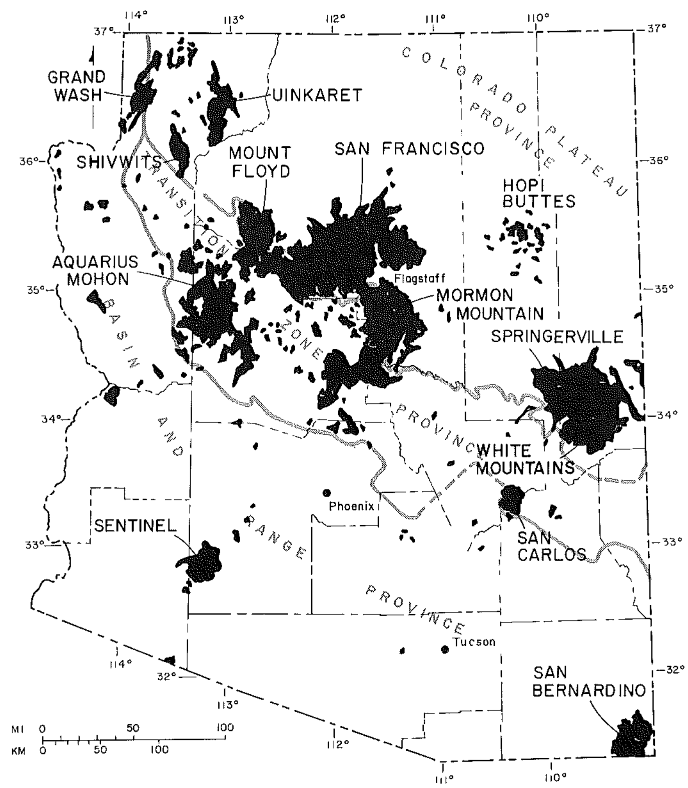
eroded volcanoes of the San Francisco Peaks and Mount Baldy in the White Mountains. The most recent basaltic volcanism, as indicated by the presence of preserved cinder cones, has been largely restricted to the San Francisco, Springerville, and Uinkaret volcanic fields of the Colorado Plateau and the Sentinel, San Bernardino, San Carlos, and Pinacate volcanic fields of the Basin and Range Province. The most recent volcanic eruption in Arizona occurred at Sunset Crater near Flagstaff between the growing seasons of 1064 and 1065 A.D. (Smiley, 1958).

During each volcanic episode described above, volcanism probably migrated in a complex manner between different parts of the State. The migration of volcanism during the two most recent volcanic episodes is illustrated in Figure 7, which shows the distribution of isotopic age determinations on volcanic and related granitic rocks for different time periods during the last 40 m.y. These maps demonstrate that volcanism resumed in southeastern Arizona approximately 30 to 40 m.y. ago and shifted westward across the State between 30 and 15 m.y. ago. At the start of the late Cenozoic volcanic episode 15 m.y. ago, volcanism progressively migrated to the northeast across the Transition Zone and into the Colorado Plateau (Figure 8). The maps also identify where the most recent volcanism has occurred and, therefore, where there may be a slight potential for future eruptions.

Figure 4. *Late Cretaceous to early Tertiary (Laramide) volcanic rocks are common in southeastern Arizona (as are the associated porphyry copper deposits), but have largely been eroded from western Arizona.*

Figure 5. *Middle Tertiary volcanic rocks are most widespread in the Basin and Range Province.*

Figure 6. *Late Cenozoic volcanics are abundant in the Transition Zone and southwestern edge of the Colorado Plateau, but are relatively sparse in the Basin and Range Province near Phoenix and Tucson.*



DISTRIBUTION OF UPPER CENOZOIC (0-15 m.y.)
VOLCANIC ROCKS AND VOLCANIC FIELDS

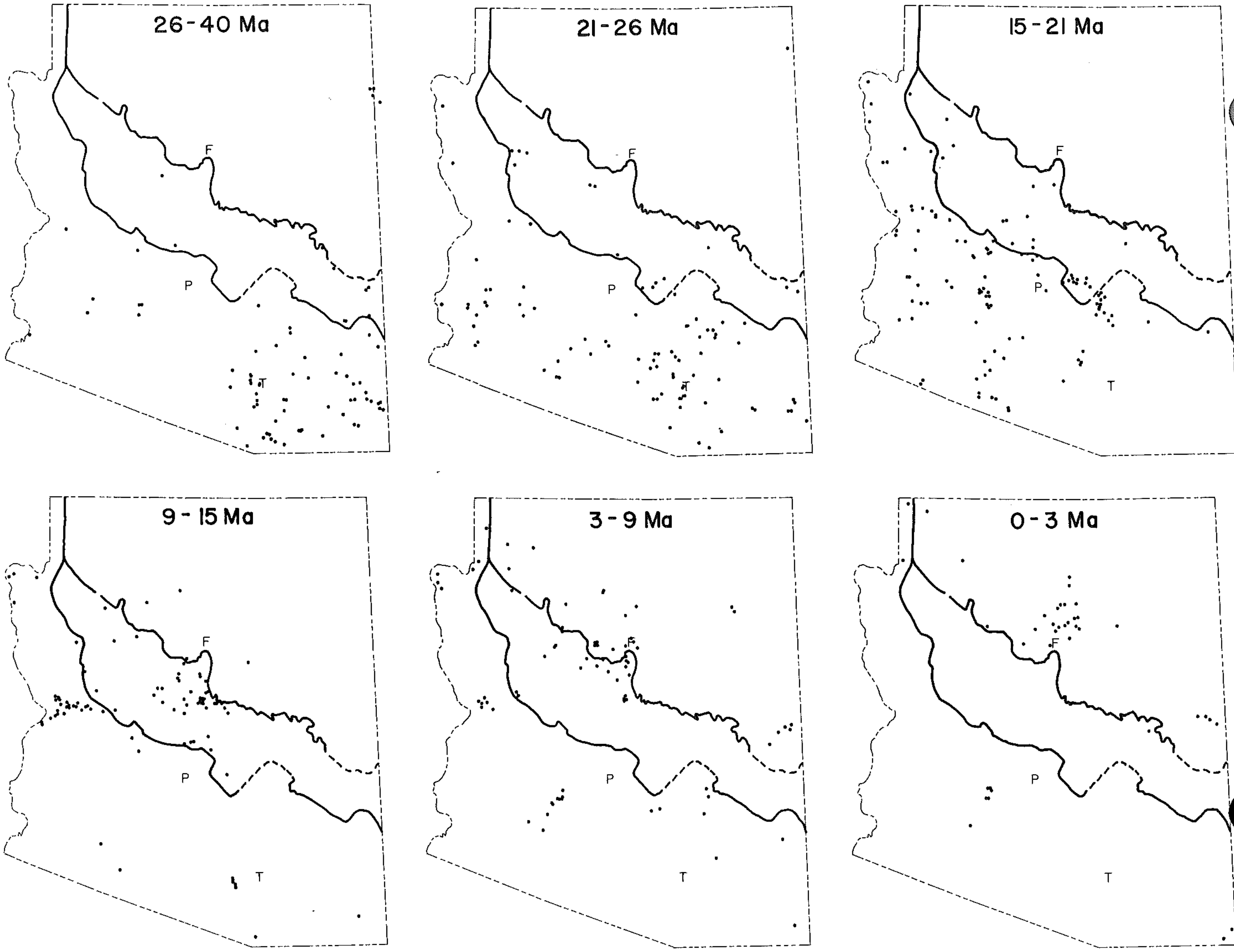


Figure 7. Distribution of isotopic age determinations on volcanic and related granitic rocks for different time periods during the last 40 m.y. These maps illustrate how volcanism migrated westward across Arizona between 40 and 15 Ma (million years ago) and then migrated northeastward toward the Colorado Plateau.

Industrial Uses of Volcanic Rocks

The six episodes of volcanism have produced a diversity of metallic mineral deposits and unusual volcanic rock types that are used as industrial products. Most precious- and base-metal ore deposits in Arizona were produced during the early Precambrian, Late Cretaceous-early Tertiary, and middle Tertiary episodes of volcanism and related emplacement of granitic magmas. In contrast, intrusion of the late Precambrian diabase magmas into the Apache Group near the Salt River Canyon and the Unkar Group in the Grand Canyon helped to form significant deposits of chrysotile asbestos, magnetite-rich iron ore, and uranium (Wrucke and others, 1986).

Of the six volcanic episodes, only the mid-Tertiary and late Cenozoic events produced rocks that are substantially exploited today. Volcanic rocks of Precambrian and Jurassic age have been so variably metamorphosed and structurally disrupted that their physical and chemical properties make them unsuitable for most commercial uses. The sole exception occurs near Mayer, where schist derived from metamorphosed rhyolite is mined for dimension stone and used in the construction industry as building facade. The qualities that made this material attractive to architects are the result of subsequent metamorphism rather than the original volcanic processes. Late Cretaceous-early Tertiary (Laramide) volcanic rocks are confined mostly to southeastern Arizona and have commonly undergone considerable hydrothermal alteration and structural deformation. Because of this, they have not been quarried for industrial use.

A variety of middle Tertiary volcanic rocks are used commercially, with those of silicic composition (at least 65 percent SiO_2 by weight) being the most important. Perlite, a rhyolitic glass that contains a concentric "onion-skin" structure caused by cooling and hydration, occurs in many parts of the Basin and Range Province. The term "perlite" has been traditionally used to describe any naturally occurring volcanic glass that expands when heated to yield a frothy, lightweight cellular substance similar in some aspects to popcorn. Perlite with excellent expansion (popping) capabilities commonly has the following properties: (1) shiny luster; (2) onion-skin texture; (3) few visible crystals; (4) presence of marekanites; (5) specific gravity (density) of approximately 2.4 g/cc; and (6) 3 to 4 percent water by weight (Wilson and Roseveare, 1945). Marekanites, obsidian nodules known as "Apache tears," are small areas of the rhyolitic glass that lack the onion-skin texture (Figure 9). The perlites of Arizona have been historically or are currently used for lightweight and high-strength aggregate, fire-retardant insulation, perlite-gypsum plaster, beverage filtrate, soil conditioner, molding for foundry sands, and filler for paints and plastics. Perlite occurrences near Picketpost Mountain southwest of Superior are of primary importance because of large potenti[al] reserves and commercial development (Peirce, 1969).

Other uses of middle Tertiary volcanic rocks include the following: (1) pumice mined by the Gila Valley Block Company northeast of

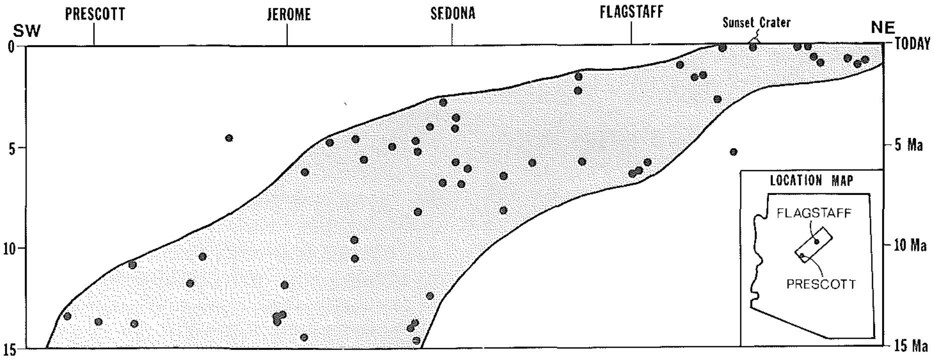


Figure 8. *Diagram shows the ages of volcanic rocks versus their geographic positions along a northeast-southwest line through Prescott and Flagstaff. Volcanism migrated northeastward during the last 15 m.y. The most recent volcanism occurred slightly northeast of Flagstaff.*

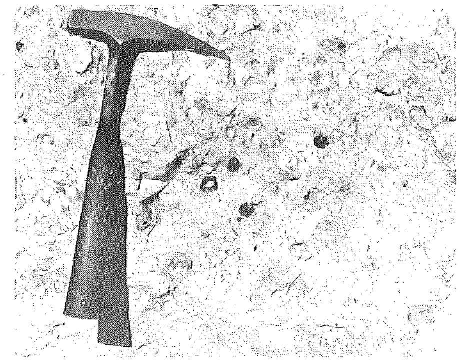


Figure 9. *View of marekanites (black spots), or "Apache tears," in a gray matrix of perlite from the Sil-Flo perlite pit west of Superior. Photo by John W. Welty.*

Safford for the fabrication of lightweight concrete block; (2) similar deposits near Kirkland in central Arizona that were crushed and sized for the production of cat litter; (3) an opaque opal known as fire agate in rhyolitic tuff near Klondyke, Graham County; and (4) basalt southwest of Casa Grande that is used in the manufacture of rock-wool insulation products.

Upper Cenozoic volcanism resulted in the development of numerous cinder cones, particularly in the San Francisco and White Mountains volcanic fields. In both of these areas, the cinders display a wide variety of colors from black to magenta. The distribution of and differences among the color types are not well understood, although the red cinders are thought to be the result of oxidation of black cinders. Cinders are mined for use as rip-rap, cinder block, aggregate for road base and asphaltic concretes, drilling-mud conditioners, drainage fields for septic systems, winter traction on icy roads, and landscaping (Figure 10). Because the Phoenix area is devoid of cinder deposits, it must import this useful material from the Colorado Plateau region. Basalt on Peridot Mesa in the San Carlos volcanic field also contains peridot, or gem-quality olivine, which is intermittently sold to rock collectors and stone cutters for jewelry or mineral specimens.

In the San Francisco volcanic field, the Sugarloaf Mountain rhyolite dome erupted 212,000 years ago (Damon and others, 1974). This eruption produced a layer of rhyolitic tuff, which yielded over 200,000 tons of lightweight, high-strength aggregate (pumice) used in the construction of Glen Canyon Dam. Currently the material is sold as lightweight aggregate and for landscaping, and Arizona Tufflite, Inc. is planning to market this material as a pozzolan. Pozzolans are siliceous materials that, when finely ground (to -325 mesh), will form a "natural" cement in the presence of water and lime. Other pozzolans are found near Williams in upper Cenozoic rocks and near Bouse and Safford in mid-Tertiary rocks.

Many volcanic eruptions are accompanied by explosive outpourings of volcanic ash, such as that erupted from Mount St. Helens in 1980. When this ash, which is composed of minute particles of volcanic glass, is deposited in a lake or other body of water, it is locally altered to useful products. Two of these products, bentonite clay and the zeolite mineral chabazite, are mined in Arizona and exported for use elsewhere. Bentonite mining in east-central Arizona began in 1924 and presently produces about 40,000 tons per year from beds of altered volcanic ash of late Cenozoic age. The bentonite is processed into desiccants, thickeners, and acid-activated clay products. The Bowie chabazite deposit of southeastern Arizona, also of late Cenozoic age, is mined for use as an activated molecular-sieve material. This deposit has yielded the largest mined tonnage of any natural zeolite in the United States, with a total product value of about $30 million since 1962.

Conclusion

Arizona has experienced a complex volcanic history that has spanned 1.8 b.y. of geologic time. In addition to helping shape the diverse and beautiful scenery of the State, volcanism and related processes are responsible for many useful products as well as much of the mineral wealth of Arizona. The large copper deposits and many gold-silver veins formed as heated fluids circulated near volcanic conduits. In addition, a variety of other commercial products such as perlite, cinders, and lightweight aggregate are currently produced from volcanic rocks. Because of the diverse ages and types of volcanism in Arizona, the potential for future production of volcanic-related commodities is great.

References

Anderson, Phillip, 1986, Summary of the Proterozoic plate tectonic evolution of Arizona from 1900 to 1600 Ma, *in* Beatty, Barbara, and Wilkinson, P. A. K., eds., Frontiers in geology and ore deposits of Arizona and the Southwest: Arizona Geological Society Digest, v. 16, p. 5-11.

Coney, P. J., and Reynolds, S. J., 1977, Cordilleran Benioff zones: Nature, v. 270, p. 403-406.

Damon, P. E., Shafiqullah, M., and Leventhal, J. S., 1974, K-Ar chronology for the San Francisco volcanic field and rate of erosion of the Little Colorado River, *in* Karlstrom, T. N. V., and others, eds., Geology of northern Arizona, with notes on archaeology and paleoclimate; pt. 1, regional studies: Geological Society of America, Rocky Mountain Section Meeting, Flagstaff, Ariz., 1974, p. 221-235.

Glazner, A. F., Nielson, J. E., Howard, K. A., and Miller, D. M., 1986, Correlation of the Peach Springs Tuff, a large-volume Miocene ignimbrite sheet in California and Arizona, *in* Cenozoic stratigraphy, structure, and mineralization in the Mohave Desert: Geological Society of America, Cordilleran Section Annual Meeting, 82nd, Los Angeles, Calif., 1986, Guidebook and Volume, Trips 5 and 6, p. 65-68.

Lipman, P. W., and Sawyer, D. A., 1985, Mesozoic ash-flow caldera fragments in southeastern Arizona and their relationship to porphyry copper deposits: Geology, v. 13, no. 9, p. 652-656.

Peirce, H. W., 1969, Perlite, *in* Mineral and water resources of Arizona: Arizona Bureau of Mines Bulletin 180, p. 403-407.

_____ 1984, The Mogollon escarpment: Arizona Bureau of Geology and Mineral Technology Fieldnotes, v. 14, no. 2, p. 8-11.

_____ 1986, Paleogeographic linkage between Arizona's physiographic provinces, *in* Beatty, Barbara, and Wilkinson, P. A. K., eds., Frontiers in geology and ore deposits of Arizona and the Southwest: Arizona Geological Society Digest, v. 16, p. 74-82.

Shafiqullah, M., Damon, P. E., Lynch, D. J., Reynolds, S. J., Rehrig, W. A., and Raymond, R. H., 1980, K-Ar geochronology and geologic history of southwestern Arizona and adjacent areas, *in* Jenney, J. P., and Stone, Claudia, eds., Studies in western Arizona: Arizona Geological Society Digest, v. 12, p. 201-260.

Smiley, T. L., 1958, The geology and dating of Sunset Crater, Flagstaff, Arizona: New Mexico Geological Society Guidebook, 9th Field Conference, p. 186-190.

Wilson, E. D., and Roseveare, G. H., 1945, Arizona perlite: Arizona Bureau of Mines Circular 12, 10 p.

Wrucke, C. T., Otton, J. K., and Desborough, G. A., 1986, Summary and origin of the mineral commodities in the middle Proterozoic Apache Group in central Arizona, *in* Beatty, Barbara, and Wilkinson, P. A. K., eds., Frontiers in geology and ore deposits of Arizona and the Southwest: Arizona Geological Society Digest, v. 16, p. 12-17.

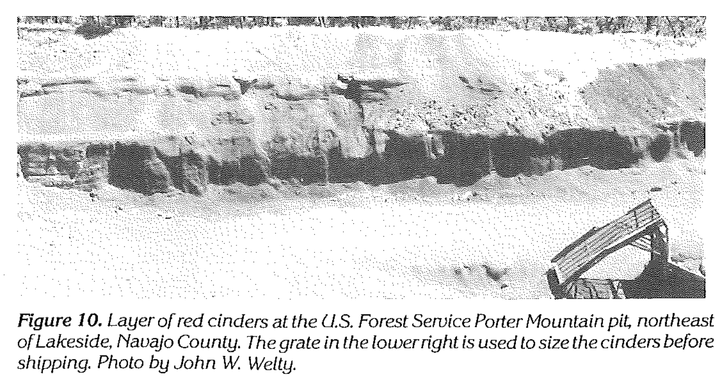


Figure 10. *Layer of red cinders at the U.S. Forest Service Porter Mountain pit, northeast of Lakeside, Navajo County. The grate in the lower right is used to size the cinders before shipping. Photo by John W. Welty.*

The Nonfuel Mineral Industry: 1985 Summary

In 1985 the value of nonfuel mineral production in the Southwest reached $5.73 billion, a slight increase from the 1984 value of $5.68 billion (Table 1). Production in the Southwest accounted for 24 percent of total output in the Nation, estimated to be $23.7 billion in 1985. For the purposes of this article, the Southwest includes Arizona, California, Colorado, Nevada, New Mexico, and Utah.

These preliminary figures were recently published by the U.S. Bureau of Mines (USBM), which has also released State-by-State estimates of nonfuel mineral production for 1985. Excerpts from the preliminary summaries for the Nation and the southwestern States appear below. Additional details on the national statistics are given in the "Significant Events" chapter of the USBM's 1986 "Mineral Commodity Summaries." Single copies are free from the Publications Distribution Section, Bureau of Mines, Cochrans Mill Rd., P.O. Box 18070, Pittsburgh, PA 15236. The Mineral Industry Surveys for individual States were prepared by State mineral specialists from the U.S. Bureau of Mines (USBM), in cooperation with the respective State mineral agencies. Lorraine B. Burgin, USBM State mineral specialist in Denver, compiled the Arizona summary, in cooperation with the Arizona Department of Mines and Mineral Resources. For copies of the preliminary reports, please write to Mineral Industry Surveys, U.S. Department of the Interior, Bureau of Mines, Washington, DC 20241.

U.S. Summary

U.S. nonfuel mineral production edged up another 2 percent in value last year to $23.7 billion, continuing its slow climb out of recession. The year's nonfuel mineral output was the basis for an estimated $244 billion worth of processed materials of mineral origin.

The gain in value occurred despite continued weak performance in the metal sector of the industry, which reflects structural changes in the Nation's economy. As the economy has become more service-oriented, demand for metals has been declining. The value of raw-metal production in 1985 fell nearly 6 percent to $5.6 billion, whereas nonmetallics posted a 5-percent increase in value to $18 billion. A key reason for this difference is that metal producers must compete mostly in international markets, whereas most producers of nonmetals supply domestic markets.

Major developments in the metal sector in 1985 included a nearly 17-percent increase in domestic mine production of gold, the only significant gainer among the metals. Mine output reached 2.4 million troy ounces, the highest since 1950, valued at about $760 million. Despite the generally low price of gold, which fluctuated between $284 and $341 per ounce, the industry expanded considerably in 1985.

Copper mine production in 1985 was 1 million metric tons, nearly the same as in the previous 2 years. Production value was estimated at $1.5 billion. Although copper prices remained at depressed levels and several mines, including the largest in the country, closed, a few firms reported profits during the year for the first time since 1981. The strength of the U.S. dollar abroad continued to hamper most of the industry.

Silver production leveled off at 43 million troy ounces, nearly the same as in 1984. The value of production, however, dropped more than 25 percent to $267 million as the average daily price of the metal fell from $8.14 to $6.20 per ounce.

Among the nonmetals, barite production increased for the second year in a row, reaching 0.9 million short tons, a 15-percent gain over 1984. Although volume was up, lower average prices resulted in a 22-percent decline in value, which was $25 million for the year.

In contrast, the value of all marketable clays produced in 1985 reached a record high of $1.1 billion. Domestic production increased 3 percent to 42.8 million tons as clay producers operated at between 60 and 90 percent of capacity all year. Despite the strong dollar, exports of clay were up for the year and the United States is expected to remain a major world supplier of high-quality clays.

About 800 million short tons of construction sand and gravel were sold or used in 1985, a 3-percent increase in volume. Value, up 9 percent, totaled $2.4 billion. Output of industrial sand and gravel reached about 29.9 million short tons worth $390 million, registering increases of 1 and 5 percent, respectively.

Output of crushed stone rose about 5 percent in 1985 to approximately 1 billion short tons valued at $4.2 billion. Dimension stone production increased 12 percent to nearly 1.3 million short tons valued at $170 million. For the fourth consecutive year, however, the value of dimension stone imports exceeded that of production.

Total U.S. demand for cement increased about 7 percent over 1984, due primarily to improved industrial, commercial, and residential construction. The value of cement production was $4.4 billion. Apparent consumption continued to rise, increasing 7 percent in 1985, a gain of nearly 25 percent over the last 3 years.

Arizona

The value of nonfuel mineral production in Arizona in 1985 was estimated at $1.5 billion,

Table 1. 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 1985 are preliminary estimates.

State	Value (thousands of dollars) 1984	1985	Percent of Total Value in 1985 Southwest	United States	Major Commodities
Arizona	1,483,479	1,532,574	26.8	6.5	copper, construction sand and gravel, cement, molybdenum, crushed stone, silver
California	2,003,445	2,217,723	38.7	9.4	cement, boron minerals, construction sand and gravel, crushed stone, sodium compounds, diatomite
Colorado	436,082	390,697	6.8	1.6	molybdenum, construction sand and gravel, cement, crushed stone, gold, zinc
Nevada	615,753	601,310	10.5	2.5	gold, silver, molybdenum, construction sand and gravel, lithium, barite
New Mexico	619,144	633,200	11.1	2.7	copper, potassium salts, molybdenum, cement, construction sand and gravel, gold
Utah	524,162	352,945	6.2	1.5	cement, copper, gold, construction sand and gravel, gilsonite, salt
SOUTHWEST	5,682,065	5,728,449	100.0	24.2	
U.S. TOTAL	23,150,000	23,712,998	—	100.0	

up 3 percent from 1984 (Table 2). Metal output accounted for about 82 percent of total value and registered a 4-percent increase from $1.19 billion in 1984 to $1.24 billion in 1985.

Arizona copper production continued to rank first in the Nation and to contribute nearly three-fourths of the State's nonfuel mineral production; however, persistent low copper prices, which were partially due to foreign competition and the strong U.S. dollar, allowed only a modest recovery from the previous year's recession. Low byproduct gold and silver prices contributed to the decline in the value of precious-metal production.

Operating copper companies increased productivity and reduced costs by revising mining and processing plans and procedures and by restructuring their organizations. Some operations remained idle and up for sale. Several companies continued studies and efforts to meet required air and water quality standards. Environmental agencies in the United States and Mexico signed a document aimed at reducing SO_2 emissions from smelters in Arizona and Mexico.

Nonmetal production, in descending order of value, included construction sand and gravel, cement, crushed stone, and lime. Increases were posted for most commodities, except cement and gypsum.

California

California remained the leading State in the Nation in the production of nonfuel minerals for 1985. Production value increased 10 percent from $2.0 billion in 1984 to an estimated $2.2 billion in 1985 (Table 1). California continued to lead all States in the production of rare-earth metal concentrate, tungsten ore and concentrate, boron minerals, diatomite, and sand and gravel. It was second in production of natural calcium chloride, portland cement, calcined gypsum, magnesium compounds from seawater, and sodium carbonate.

Colorado

The value of nonfuel mineral production in Colorado in 1985 was estimated at $390.7 million (Table 1). This decrease of 10 percent from the 1984 value of $436.1 million resumes the declining trend begun in 1981 that was interrupted by a brief upturn in 1984. A virtual shutdown of Colorado's precious metals industry, owing to low prices and corporate restructuring, accounted for most of the decline in output.

Of the State's major base- and precious-metal mines, only one operated throughout the year. Low prices and weak markets for metals were the major factors in mine closures. Other commodities whose reduced production contributed to the total value decline include vanadium, cement, and crushed stone. Interest in exploration and development remained high, however.

Molybdenum, still Colorado's leading nonfuel mineral, accounted for less than one-half of the State's total value of nonfuel minerals in 1985.

Table 2. 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 1985 are preliminary estimates.

Mineral	Value (thousands of dollars) 1984	1985
Clays	819	1,228
Copper	1,100,182	1,133,233
Gem stones	2,700	2,700
Gold	18,591	W
Gypsum	2,332	2,191
Lime	17,304	22,977
Molybdenum	76,112	76,423
Pumice	21	22
Sand and gravel (construction)	101,959	122,900
Silver	33,320	24,338
Stone		
Crushed	27,300	29,800
Dimension	2	1
Other*	102,839	116,761

W Withheld to avoid disclosing company proprietary data; value included in "other" figure.

* Combined value of cement, lead, perlite, pyrites, salt, industrial sand and gravel, tin, and value indicated by symbol W.

Nevada

Nevada's production value of nonfuel minerals in 1985 was estimated to be $601.3 million, a decrease of $14.4 million from that recorded in 1984 (Table 1). The decline resulted from lower prices for gold and silver during the year, despite an increase in the production of gold from 998,000 troy ounces to 1,120,000 troy ounces. Nevada continued to lead the Nation in the production of gold and barite, and was the sole producer of mined magnesite and mercury. Based on preliminary statistics, Nevada ranked 12th in the Nation in the value of its 1985 nonfuel mineral production.

New Mexico

The value of nonfuel mineral production in New Mexico in 1985 was estimated to be $633.2 million, about 2 percent higher than in 1984 (Table 1). Estimated output and value of portland cement, copper, gold, gypsum, salt, and construction sand and gravel increased over those of 1984. Estimated output and value of potash declined 19 percent and 22 percent, respectively.

Early in 1985, the Department of Labor granted $600,000 to New Mexico for retraining copper and steel workers displaced by plant and mine closings.

Utah

The value of nonfuel mineral production in Utah declined to $352.9 million in 1985 (Table 1). Metal production declined from more than half of the total value of nonfuel minerals produced in 1984 to about one-third in 1985 because of persistent low metal prices and the shutdown of the State's principal producer of copper, gold, molybdenum, and silver.

The value of nonmetal production rose in 1985. Leading commodities in the group include portland cement, construction sand and gravel, gilsonite, salt, phosphate rock, crushed stone, and lime.

GOLD NUGGETS

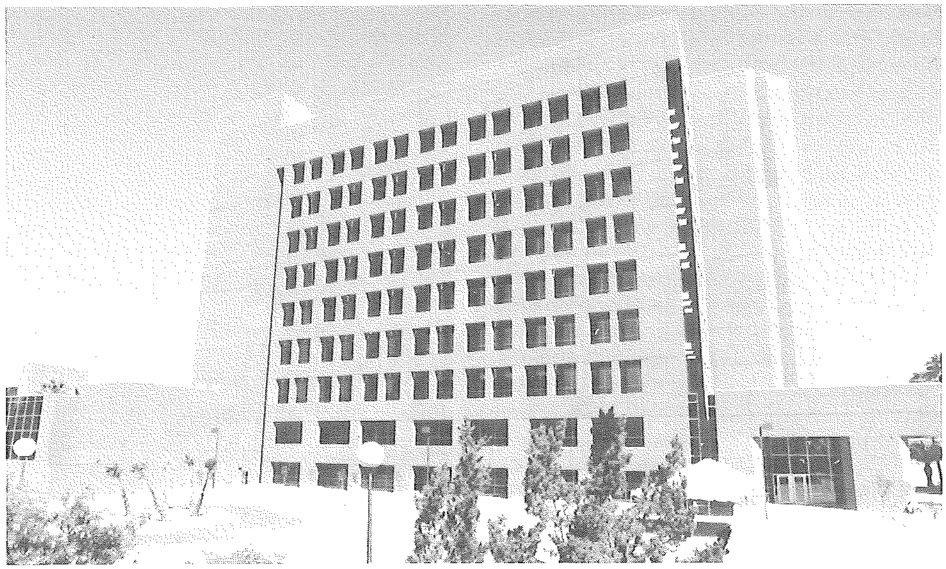
The troy system of weights, used in the United States for gold and other precious metals, is based on the troy ounce of 480 grains or 20 pennyweight. Many nations use the metric system of measurement or a combination of the two systems. One troy ounce is equivalent to 1.097 avoirdupois ounces or 31.1035 grams. One kilogram (1,000 grams) is equivalent to 32.1507 troy ounces. Exploration geologists often refer to gold concentrations in parts per million. One part per million is equivalent to one gram per metric ton.

Fineness refers to the weight proportion of pure gold in an alloy, expressed in parts per thousand; 1000 fine gold is 100 percent pure gold. The term "karat," like fineness, refers to purity, but is expressed in 24ths; thus 24-karat (24k) gold is 1000 fine or pure gold, and 14k gold is 14/24 or 58.3 percent gold. Any item with less than 41.2 percent gold (10k) cannot be called "karat gold." Placer gold generally contains 11.4 to 21.4 percent (810 to 890 fine) gold. Gold alloys contain elements such as copper, silver, or zinc, which are added to give strength or color.

Mines in Arizona have produced more than 14.2 million troy ounces of gold from the 1880's through 1984.

Gould-Simpson Building Honors Two Distinguished Scientists

by Orlo E. Childs



The Gould-Simpson Science Building was dedicated at the University of Arizona on March 21, 1986. This 10-story building, the tallest on campus, contains 214,000 square feet of classroom, laboratory, and office space.

A university shares the honor when it designates outstanding members of its own faculty for special recognition. The long-awaited formal dedication of the Gould-Simpson Science Building on the campus of the University of Arizona took place on March 21, 1986. Some classrooms and laboratories were already in use this semester; by early summer, the geosciences department will complete its move into the first five floors of this magnificent 10-story building. At a cost of $18.45 million, this 214,000-square-foot building will serve all disciplines of the geosciences department, along with faculties and students of the molecular biology, plant science, and computer science departments. Dr. Henry Koffler, president of the University of Arizona, emphasized at the dedication ceremony that the building is tangible evidence of the university's commitment to education and research in science and to service to the State and Nation. In such a commitment, it is highly appropriate that the building should be named after two university professors who have attained national and international reputations as leaders and pioneers in science.

Dr. Laurence McKinley Gould was characterized as an explorer of space, a reference to his role as principal scientist on the first Byrd expedition to the South Pole in 1928. Dr. George Gaylord Simpson was described as an explorer of time, whose life-long pursuit of knowledge in zoology and paleontology, particularly his study of mammals, has resulted in more than 700 publications.

It is interesting to recall that the University of Arizona honored these friends and internationally known scholars when both were given honorary doctorates at the annual commencement in May 1982. It is regrettable that Dr. Simpson did not live to see the completion of the science building that bears his name along with that of his friend and colleague. As the university recognizes two of its well-known faculty and dedicates its new building to the "tradition of good science which has dominated the lives of Dr. Gould and Dr. Simpson," it seems particularly appropriate that the naming of that building will perpetuate the memory and scholarly example of two close personal friends.

Dr. Laurence McKinley Gould and Dr. Ann Roe Simpson, widow of Dr. George Gaylord Simpson, at the dedication of the Gould-Simpson Science Building. Two hundred persons attended the ceremony.

The following speech was given at the dedication of the Gould-Simpson Science Building.

by George H. Davis

Professor of Geosciences and Vice Provost
University of Arizona

Laurence McKinley Gould and George Gaylord Simpson — giants in the enterprise of teaching and scholarship — appropriate names indeed for a giant of a building whose mission is nourishing the development of emerging young scientists and discovering new scientific knowledge through original research. Some might look at the name "Gould-Simpson Building" and conclude that the University of Arizona could not decide whether to call the new science building the Gould Building or the Simpson Building; a compromise must have been struck. If this were the case, I would reveal it instantly by beginning at once to recite the astounding accomplishments of each of these men, one by one, first Gould, then Simpson, discrete and separate. I have no intention of doing that just yet.

Instead I want to draw attention to the significance and importance of the hyphen in the name "Gould-Simpson Building." For you see, the hyphen symbolizes the bond, the relationship, the oneness that so many of us recognize as utterly fundamental to the significance of naming this building the Gould-Simpson Building.

The bond I refer to is one of many dimensions. It is a bond of friendship — enduring friendship between two colleagues who simply enjoyed one another's company. It is a bond of intellectual connection between two professors utterly committed to the enterprise of higher learning. It is a bond that joins the immense creative scholarship of a Simpson with ingredients out of which heroes are born, in Gould, the explorer, teacher, educator, and, I might add, prime mover in the harnessing of science to the good of mankind. The hyphen, then, is very important, for it calls attention to the conditions under which universities operate at the highest level: close relationships among colleagues and between students and faculty, born out of mutual respect and a sense of commitment to higher learning; and the perfect blend, the perfect mix, between research and teaching and service to others, all carried out at the highest level. Gould-hyphen-Simpson: a perfect banner for this building.

Having made clear the connection, I think it might be safe to take stock of the accomplishments of these men, individually.

In 1929 Dr. Laurence McKinley Gould, second-in-command of the historic Richard E. Byrd expedition to Antarctica, led a remarkable 2 ½-month, 1,500-mile dog-sledge journey to explore and collect samples of the last terrestrial frontier. Dr. Gould was, in fact, the first American geologist to set foot on Antarctica. He recounts the adventure in his book *Cold,* first published in 1931, and recently republished in 1984, with an epilogue in which he calls for the conservation of Antarctica as an environment free from international rivalry and commercial exploitation, a laboratory preserved for scientists of all nations.

His degrees were taken at the University of Michigan. In 1932 he joined the faculty of Carleton College, founded the department of geology and geography, and in 1945 became president of Carleton, serving through 1962. A former Carleton student described him this way: "Preeminently a scientist fascinated by the pursuit of truth and knowledge, he has the spirit of the scholar, the soul of the poet and adventurer, and a special ability to communicate his passion for learning to his students."

Dr. Gould came to the University of Arizona in 1963, serving as professor of geosciences until 1978, when he "retired" to emeritus professor. Along the way, he laid the foundation for establishment of the College of Earth Sciences.

The full import of Dr. Gould's various roles may be seen in his numerous honors, awards, and degrees. For example, he is noted for his work as director of the monumental U.S. Antarctic scientific research program during the 1957-58 International Geophysical Year, for which he received the Distinguished Public Service Medal, the highest award the Navy confers on a civilian. He served as president of the American Association for the Advancement of Science and president of the United Chapters of Phi Beta Kappa. He has received more than 30 honorary doctoral degrees.

George Gaylord Simpson is celebrated as one of the founders of modern evolutionary theory, a distinguished leader in the fields of vertebrate paleontology, geology, biology, and ecology. Dr. Simpson was without peer in the world in the study of fossil mammals. He possessed what he described as an "uncontrollable desire to know and understand the world in which he lived." This is reflected dramatically in his publications, which number 700 and more, the outgrowth of 60 years of studying, teaching, writing, and lecturing about everything from the evolution of man to the history of biology to the eating habits of penguins. His books are major works and they target fundamental concepts and issues: *The Major Features of Evolution; The Meaning of Evolution; A Study of the History of Life and of Its Significance for Man; This View of Life: The World of an Evolutionist.* These are profound themes that few scholars would, or could, dare address.

While his major field expeditions focused on the regions of western North America and

Dr. and Mrs. Laurence M. (Peggy) Gould.

South America, his explorations took him to Africa, Europe, Australia, New Zealand, the Arctic, and the Antarctic. His 1953 expedition in Colorado resulted in eight skulls of Eohippus, the dawn horse, whose descendants include modern horses.

Dr. Simpson received his degrees from Yale. He served 32 years at the American Museum of Natural History, the most prestigious paleontological research institution in North America, where he held the positions of curator, chairman of the department of vertebrate paleontology, and dean of the faculty. He also served as professor of zoology at Columbia University from 1945 to 1959 and was for 10 years the Alexander Agassiz Professor of the Museum of Comparative Zoology at Harvard University. It was in 1967 that he joined the faculty of the University of Arizona, where he continued his teaching and research and provided inspiration and guidance to graduate students in geosciences across the campus community.

Among his numerous awards, honors, and degrees are the President's National Medal of Science, the Penrose Medal of the Geological Society of America, the Thompson and Elliot Medals of the National Academy of Science, the Darwin Medal of the Royal Society of London, the Smithsonian Institution's first International Award for Distinguished Contribution to Natural History, and some 13 honorary degrees.

Gould-hyphen-Simpson: two distinguished persons who had made enormous contributions before coming to the University of Arizona and who, upon coming, were, if I could borrow a phrase, "never at rest." Through their leadership and their example, Laurence McKinley Gould and George Gaylord Simpson helped to pioneer a thrust in science on this campus whose momentum we feel so clearly today.

Dr. Gould. Mrs. Simpson. We are so grateful. And in that gratitude we intend to carry out our work at this university at the highest level that we can manage — 10 stories high and more.

New Bureau Publications

Scarborough, R. B., 1986, Map of mid-Tertiary volcanic, plutonic, and sedimentary rock outcrops in Arizona: Arizona Bureau of Geology and Mineral Technology Map 20, scale 1:1,000,000; $3.00, plus $1.75 for postage and handling.

Middle Tertiary rocks are widespread in the Transition Zone and Basin and Range Province. Map 20 identifies the igneous outcrops in the State and shows the distribution of related sedimentary rocks, some of which contain large, low-grade uranium deposits. This map is useful in the search for mineral deposits related to mid-Tertiary processes.

Scarborough, R. B., Menges, C. M., and Pearthree, P. A., 1986, Map of late Pliocene-Quaternary (post-4-m.y.) faults, folds, and volcanic outcrops in Arizona: Arizona Bureau of Geology and Mineral Technology Map 22, scale 1:1,000,000; $3.00, plus $1.75 for postage and handling.

Map 22 identifies the regions of youngest faulting and volcanism in Arizona, and thus, the areas believed to be most subject to the hazards associated with a renewal of these processes. These areas are mostly confined to the Colorado Plateau and Transition Zone physiographic provinces. Map 22 is also helpful in locating the younger volcanic rocks that are most often exploited for industrial uses. Rocks in the Flagstaff and Show Low areas, for example, are being quarried for cinders, which are used in landscaping and road surfacing, as noted in the feature article of this issue.

Schnabel, Lorraine, and Welty, J. W., 1986, Bibliography for metallic mineral districts in Cochise, Graham, and Greenlee Counties, Arizona: Arizona Bureau of Geology and Mineral Technology Circular 24, 38 p.; $4.00, plus $1.75 for postage and handling.

This circular provides references for each known metallic mineral district in Cochise, Graham, and Greenlee Counties in Arizona. It is the first in a series of county-by-county bibliographies. Nearly 800 citations are included. Mineral districts are listed alphabetically; those with no reported production are included as well.

Early Proterozoic Geology of Arizona

by Clay M. Conway and *Karl E. Karlstrom*
U.S. Geological Survey — Northern Arizona University

Arizona is one of the few States in the United States that has a relatively large exposure of Proterozoic rocks (Figure 1), which, with Archean rocks, compose most of the North American crust. The broad belt of Early and Middle Proterozoic rocks in the Transition Zone is perpendicular to regional Proterozoic trends and contains representatives of several major transcontinental belts. Analysis of these belts and their interrelations in Arizona is yielding new insights into the Proterozoic crustal evolution of the southern margin of the North American craton. The endowment of massive sulfides and other ore deposits in Precambrian rocks has ranked next to the porphyry coppers in economic importance in Arizona. The metallogeny of the Proterozoic terrane is a promising and rapidly developing topic of study.

In recent years, expanded interest in Arizona's Precambrian history has accompanied a general upsurge in studies on the evolution of continental crust. This interest was reflected by the attendance of 73 geoscientists at a workshop on the Early Proterozoic of Arizona, held in Flagstaff October 3-5, 1985. The conference was convened by the authors and Leon T. Silver [California Institute of Technology (Caltech)] and sponsored by the U.S. Geological Survey (USGS), Northern Arizona University (NAU), Caltech, and the Arizona Bureau of Geology and Mineral Technology. This summary of the workshop proceedings emphasizes recent findings and current studies in Arizona.

Silver has defined a geochronologic (U-Pb zircon) boundary extending from central Arizona into northern New Mexico between an older northern province (1.7-1.8 b.y.) and a younger southern province (1.6-1.7 b.y.). Investigations into the physical nature of the boundary are yet inconclusive and were a major subject of the workshop. In Arizona the boundary between the two provinces can be simply defined by the Moore Gulch fault (MG, Figure 1), but we show a broad boundary zone in Figure 1 to reflect the presence of minor exposures of southern-province affinity northwest of this fault and northern-province affinity south of the fault.

Overview

Silver opened the workshop by suggesting that 1740- to 1780-m.y. submarine volcanic-sedimentary successions in the northern province represent primitive island arcs and interarc basins. Vast batholiths intruded the northern province between 1690 and 1750 m.y. ago. This plutonism has temporal overlap, and physical overlap in central Arizona, with volcanism and hypabyssal magmatism in the southern province (1680-1710 m.y. ago). Scattered plutonism occurred in the southern province between 1610 and 1640 m.y. ago. Silver speculated that volcanism and associated sedimentation in the southern province occurred in a basin system, with high-silica rhyolite calderas and a transgressive sandstone facies to the north, and fore-arc deep-water turbidites to the south.

Clay Conway (USGS, Flagstaff) cited evidence for contemporaneous quartz-arenite sedimentation and alkali-rhyolite ash-flow volcanism in the Mazatzal Mountains-Tonto Basin area of the southern province. He noted local unconformable relationships between the continental succession containing quartz arenite and rhyolite and an underlying calc-alkaline complex of diorite, basalt, and graywacke. Based on these observations, Conway suggested that the local calc-alkaline rocks, together with the calc-alkaline Yavapai Series and batholiths of the northern province, constituted a basement to the continental supracrustal pile. He further suggested that the Texas Gulch Formation, which rests unconformably on plutonic and stratified rocks of the northern province in the Bradshaw Mountains, belongs to the southern province.

Kent Condie [New Mex. Inst. of Mining and Tech. (NMIMT)] viewed the northern-province sequences in Arizona, New Mexico, and Colorado as consisting of bimodal, submarine volcanic rocks, and the southern-province sequences as consisting of submarine or terrestrial sedimentary rocks and chiefly bimodal volcanic rocks. The andesite-rich volcanics of the Yavapai terrane in Arizona were considered an anomaly in the northern terrane. Condie suggested that the Pinal strata of the southern province consist of an eastern volcanic-sedimentary facies and a western sedimentary facies.

Phillip Anderson (Precambrian Research and Exploration Inc., Payson) suggested that Early Proterozoic rocks in Arizona comprise three major northeast-trending belts: a northwest 1.9- to 2.0-b.y.-old paragneiss belt, a central 1.7- to 1.8-b.y.-old volcanic belt (Bagdad to Tonto Basin), and a southeast 1.7-b.y.-old paraschist belt. He reported that the central volcanic belt contains the following: progressively younger rocks from northwest to southeast; low-angle unconformities that indicate local onlap of one volcanic pile by another; unconformities resulting from unroofing of plutons and infilling of successor sediments in troughs (e.g., Texas Gulch Formation); and chemical polarities that suggest early subduction to the southeast, with a flip about 1740 m.y. ago and subsequent subduction to the northwest.

Karl Karlstrom (NAU) contrasted mostly brittle deformation of the southern province with mostly ductile deformation of the northern province. Deformational fabric in the Mazatzal Mountains is characterized by low-angle thrusts with stair-step geometry, whereas recumbent folding in the Bradshaw Mountains is apparently associated with deep

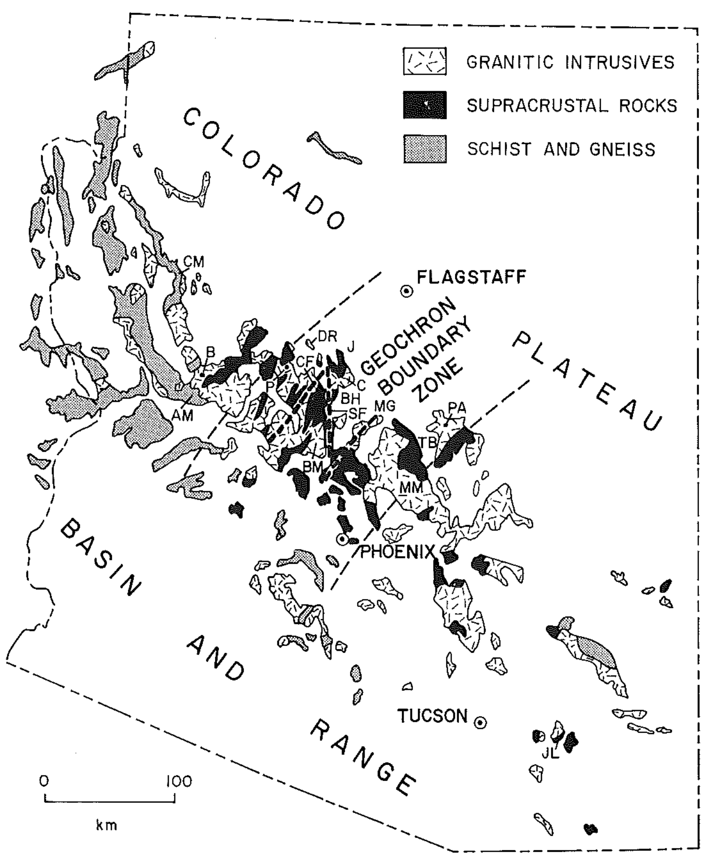


Figure 1. Distribution of exposed Early and Middle Proterozoic rocks in Arizona. The geochronological boundary is between a 1.69- to 1.78-b.y. province to the northwest and a 1.62- to 1.71-b.y. province to the southeast. The geochron-boundary zone contains lithologic groups of both provinces. Anorogenic 1.4-b.y.-old granites are scattered throughout the State and are included in the granitic intrusives unit of this figure. Abbreviations: AM - Arrastra Mountains; B - Bagdad; BH - Black Hills; BM - Bradshaw Mountains; CF - Chaparral fault; CM - Cottonwood Mountains; DR - Del Rio; J - Jerome; JL - Johnny Lyon Hills; MG - Moore Gulch fault; MM - Mazatzal Mountains; P - Prescott; PA - Payson; SF - Shylock fault; TB - Tonto Basin.

thrusting. Karlstrom suggested that similar northwest vergence in these areas indicates similar crustal interactions that operated over a long time and produced different effects at different crustal levels. He further suggested that some boundaries between rock assemblages in Arizona (e.g., the Shylock fault zone) may be structurally complex features such as rotated and reactivated thrust faults.

Northern Province Studies

Karlstrom, Pat O'Hara (Kaaterskill Exploration, Prescott), and Sue Beard (USGS, Flagstaff) concluded that two episodes of deformation occurred in the Texas Gulch Formation and unconformably underlying Yavapai strata and Brady Butte Granodiorite, as evidenced by two generations of coaxial folds. Researchers disagreed about why the folds have shallow plunges above the granodiorite and why they steepen away from the pluton. There is no structural evidence for deformation predating deposition of the Texas Gulch Formation. In the Ash Creek Group near Jerome, Paul Lindberg (consultant, Sedona) found that major folds plunge steeply to the north and have been cross-folded on east-west axes. This apparently differs from the two-stage coaxial deformation of the Bradshaw Mountains.

Gordon Swann (USGS, Flagstaff) reviewed Landsat imagery of major shear zones in the northern province, noting the prominence of the Moore Gulch fault and a major zone in the Weaver Mountains that could be a southwest extension of the Chaparral fault. O'Hara showed evidence of large-scale truncations along faults in the Shylock shear zone that he speculated could be rotated thrust faults. Marc Darrach (NAU) found steep lineations in the Shylock zone, and from S-C fabric studies and rotated porphyroclasts, he noted consistent indications of east-side-up translations on shear planes over a wide zone. In contrast, Becky Williamson (NAU) found evidence for dextral strike-slip translation from S-C relations in mylonite of the Chaparral fault zone.

O'Hara reported that highly sinuous isograds in the pelitic rocks of the Big Bug Group north of the Crazy Basin Quartz Monzonite are the result of east-west sharp-gradient reversals in PCO_2 during regional metamorphism. He also concluded that the general up-gradient change toward the late syntectonic(?) Crazy Basin pluton was the result of doming of the isograds by intrusion of the pluton.

Lindberg presented a detailed reconstruction of the stratigraphy at Jerome and a model of sea-floor caldera formation, chloritic, hydrothermal alteration in a root zone, and exhalation of sulfides that formed the giant United Verde massive-sulfide deposit. Mae Gustin and Nancy Johnson (Univ. of Ariz.) reported preliminary results of petrochemical and isotopic studies of ores, other exhalative rocks, and altered rocks at the United Verde and nearby Copper Chief mines, respectively.

Beard determined that an upper greenschist- to lower amphibolite-grade section in the Cottonwood Mountains of western Arizona consists of thick basalt overlain by felsic volcaniclastic rocks and sedimentary rocks. This section, which is characterized by a tectonite fabric with lineation aligned parallel to the plunge of minor fold axes, contains evidence for only one deformational event.

Bruce Bryant (USGS, Denver) reported on his mapping of plutonic bodies and screens of stratified rocks in the Poache Mountains, southwest of Bagdad. U-Pb zircon dating by Joe Wooden (USGS, Menlo Park) indicates that several undeformed porphyritic granitic plutons are about 1415 m.y. old, but the petrographically similar granite of Signal Peak is 1690 m.y. old. Ages of 1706 and 1710 m.y. on deformed granodiorite and screens were interpreted to represent a time of metamorphism and deformation.

Conway suggested that the overturned basalt-rhyolite sequence at Bagdad is structurally simple and that the hosted massive-sulfide deposits occur mostly on the flanks of a felsic volcano. He further suggested that alaskite/granophyre sills that intrude the base of the section drove hydrothermal activity, which resulted in widespread alteration and formation of sea-floor, exhalative, massive-sulfide deposits. Lori Robison (USGS, Flagstaff) presented a model for hydrothermal activity that resulted in widespread mobilization of many elements, notably a nearly complete depletion of Cu in basalt beneath the Old Dick and Copper Queen ore bodies.

Southern Province and Boundary Studies

Steve Maynard (Univ. of New Mex.) described the Moore Gulch fault and juxtaposed rocks in the New River Mountains (Figure 1). He noted that rocks on the northwest side of the fault have affinity to Yavapai strata and associated plutons, whereas those on the south side are similar to felsic volcanic and hypabyssal rocks of the Tonto Basin-Mazatzal Mountains area.

Larry Middleton (NAU) reported that an exposure of southern-province Mazatzal Quartzite, isolated within the northern province in Chino Valley, consists of coarse fluvial conglomerates deposited as gravel bars on alluvial fans.

Dave Puls (NAU) described ramp and duplex thrust structures and thrust-produced folds in the Mazatzal Mountains. He presented arguments for a minimum of 20 km of northwest-directed thrusting. Julie Roller (NAU) reported on a spectrum of minor fold attitudes, boudinage, rootless folds, and other indicators of transposition in a relatively incompetent section of the Alder Formation in the Mazatzal Mountains. She cautioned that stratigraphic succession was difficult to determine in these rocks.

A zone of disrupted graywacke blocks in a shale matrix in the Pinal Schist of the Dragoon Mountains, as interpreted by Peter Swift (Univ. of Ariz.), resulted from major movements along fault zones prior to regional deformation. He noted similarities in rock fabric between these rocks and the classic Franciscan melange of California.

From comparisons of trace-element data from the Pinal Schist with trace-element treatments in modern magmatic provinces, Pete Copeland (NMIMT) suggested that the Pinal strata were formed in a marginal continental arc or associated back-arc environment. Rob Reed (NMIMT) reported that the quartzites and sandstones in the Alder Group of the Mazatzal Mountains appear to be craton derived and the subgraywackes appear to be of arc origin. Trace elements indicate that the basalt in the Alder Group originated either in a continental or continental margin setting.

Topaz in a rhyolite unit of the Alder Formation in the Tonto Basin is probably secondary, reported Winnie Kortemeir (Ariz. State Univ.). It is closely associated with unfoliated quartz-white mica-topaz dikes(?) and with beryl- and topaz-bearing veins in shear zones.

Regional Studies

Two distinct suites of Middle Proterozoic (1400-1450 m.y.) anorogenic granites in Arizona serve as probes of the Early Proterozoic crust at depths of 25 to 37 km, according to Lawford Anderson (Univ. of Southern Calif.). Peraluminous, two-mica, monazite-bearing granites in central and southeastern Arizona and marginally peraluminous to metaluminous, biotite-sphene ± hornblende, fluorite-bearing granites in western Arizona and southwestern California reflect two fundamentally different deep crustal regimes. These regimes are not reflected by known lithologic and age provinces.

Neodymium isotope data reported by Don DePaolo (Univ. of Calif., Los Angeles) suggest that three Early Proterozoic crustal provinces exist in Arizona and neighboring States. Model crust-formation ages (not ages of crystallization) are 1.7 to 1.8 b.y. in central Arizona, 1.8 to 2.0 b.y. in northwestern Arizona, and 2.0 to 2.3 b.y. for extreme western Arizona, southeastern California, and southern Nevada. The relation of these provinces to geochronologic provinces is obscure, although boundaries appear to be parallel. Metaluminous 1.4-b.y.-old granites are largely within the 2.0- to 2.3-b.y.-old crust, and peraluminous 1.4-b.y.-old granites are largely within the 1.7- to 2.0-b.y.-old crust.

Common-lead work by Wooden indicates a crustal terrane in the Mojave Desert with an Archean component similar to that found in northern Utah, and a terrane in Arizona, New Mexico, and southern Colorado with no Archean component. These results agree with the Nd isotope data in requiring at least two Proterozoic crustal provinces in the Southwest, one containing little or no recycled Archean crust. Wooden and Geoff Elliot (USGS, Menlo Park) reported that 1690- to 1975-m.y.-old zircons from a high-grade terrane in the New York Mountains of southeastern California may represent episodic disturbance, at about

1700 m.y., of zircons as old as 2000 m.y., the oldest zircon ages presently known in the southwestern United States.

Condie reported that northern-province basalts in Arizona, New Mexico, and Colorado are geochemically similar to modern evolved island-arc or continental back-arc basalts and are clearly different from within-plate basalts. In contrast, southern-province basalts and felsic volcanics are like modern continental volcanics in trace-element character. Condie suggested that the common bimodality of the northern-province volcanic rocks resulted from eruption of basalts in subaqueous back-arc basins and transport into these basins of contemporaneous felsic ash flows or Plinian tuff from adjacent arcs.

Sam Bowring (Washington Univ.) reported progress on U-Pb dating of zircons from a number of Arizona samples collected to study mechanisms of continental accretion and Proterozoic orogeny.

Summary

Silver commended the directions taken by workshop participants and stressed the need for all to view their projects in the broad framework of the growth of the North American craton. Gordon Gastil (San Diego State Univ.) emphasized the need for a perspective on global crustal evolution in the course of regional studies. Paul Damon (Univ. of Ariz.) stressed the need for collaboration among workers from various disciplines, applauded the cooperative spirit of the workshop, and called for a round of applause for Silver, "the grand old man of the Precambrian of Arizona."

Several important conclusions can be drawn from recent work on the Proterozoic of Arizona. The U-Pb geochronological boundary (Figure 1) that extends eastward across most of the continent may be best exposed and best defined in central Arizona, although its nature remains controversial. It is no longer just a geochronological boundary, but is further defined by contrasts in sedimentation, magmatism, and mineralization. Basically, the northern province is a collage(?) of island-arc materials, whereas the southern province is fundamentally a cratonic to continental-margin suite. The boundary is structurally complex and is distributed across a broad zone. Many problems remain and their resolution will require integration of data from various disciplines.

PUBLICATIONS

Appraisal Manual for Mines and Natural Resources, Arizona Dept. of Revenue, 1986, 47 p. This guide, to be used for the 1986 tax year, discusses techniques and procedures that are designed to assist the appraiser in the application of income, cost, and market approaches to valuation of natural resource property. The procedures conform to the recently adopted mine valuation regulations. The manual is free to government agencies; to others, the cost is $25.00 per copy. Contact Donald E. Ross, Arizona Dept. of Revenue, P.O. Box 29014, Phoenix, AZ 85038.

Geology of Central and Northern Arizona, J. D. Nations and others, eds., 1986, 176 p. This field trip guidebook for the Geological Society of America Rocky Mountain Section Meeting in Flagstaff covers a broad spectrum of geologic topics from ore deposits to vertebrate paleontology. It provides the most current data and latest interpretations for the geology of the area. Copies are available, for $15.00 each, from the Geology Dept., Box 6030, Northern Arizona Univ., Flagstaff, AZ 86011.

Oil and Gas Conservation Commission. A free list of publications can be obtained from the Commission at 1645 W. Jefferson Ave., Phoenix, AZ 85007.

PROFESSIONAL MEETINGS

Planet Mercury. Meeting, August 6-9, 1986, Tucson, Ariz. Contact Mildred Matthews, Lunar & Planetary Laboratory, University of Arizona, Tucson, AZ 85721; (602) 621-2902.

Southwestern Geology and Paleontology. Annual symposium, September 6, 1986, Flagstaff, Ariz. Contact 39th Symposium Secretary, Dept. of Geology, Museum of Northern Arizona, Rt. 4, Box 720, Flagstaff, AZ 86001; (602) 774-5211.

Fieldnotes

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