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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.

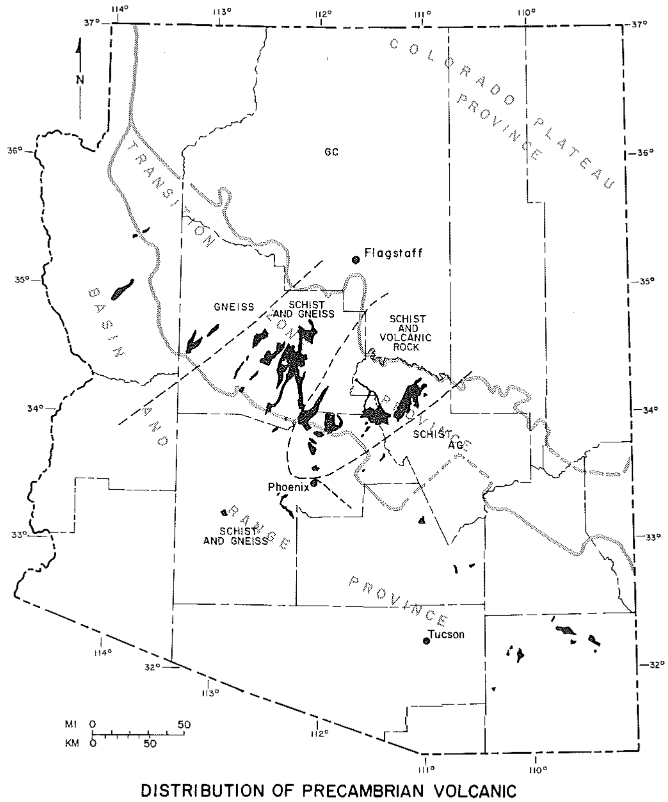


Figure 2. *Outcrops of Precambrian and metamorphosed volcanic rocks formed during the first volcanic episode (1.6-1.8 b.y. ago) are shown in black. Deformation and metamorphism under high temperatures and pressures have generally converted these volcanic rocks into schist or gneiss. Outcrops of rocks 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).*

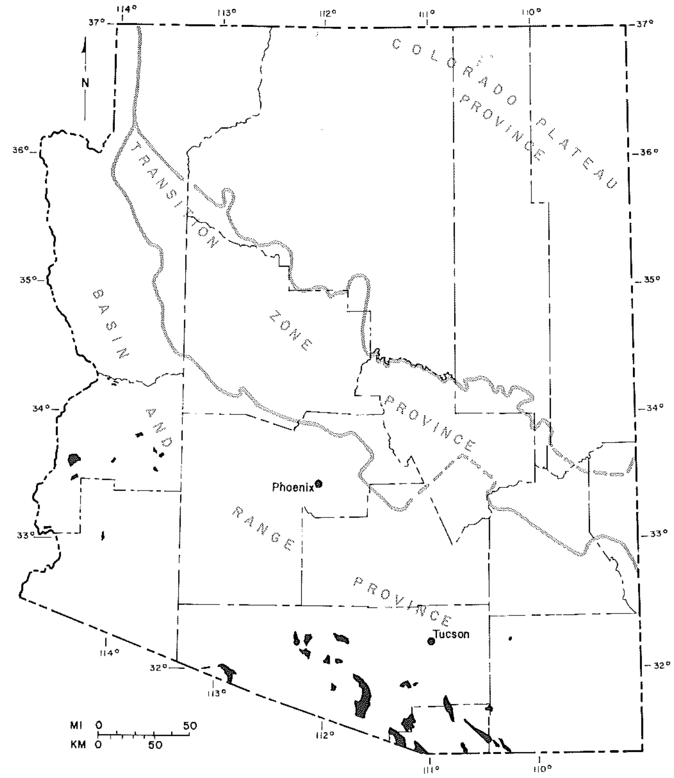


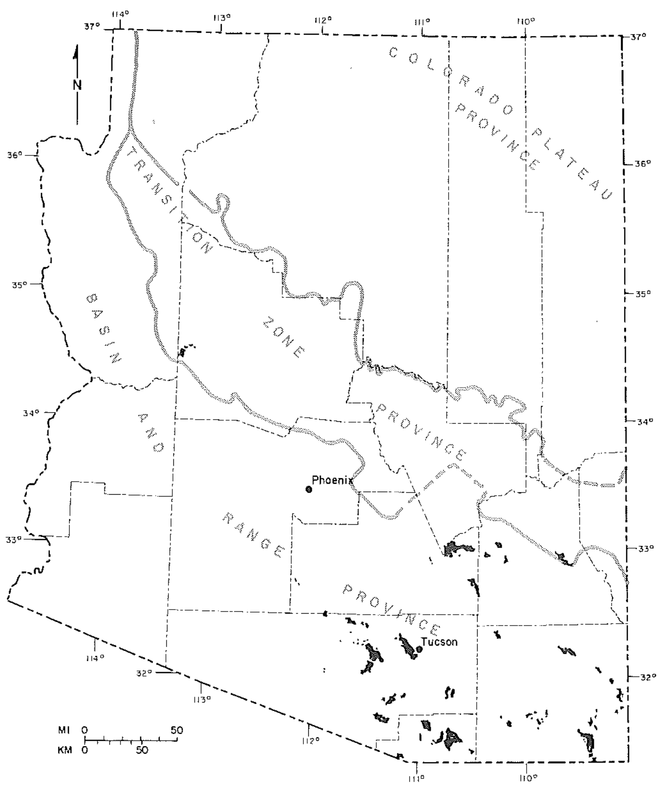
Figure 3. *Outcrops of Jurassic volcanic rocks occur in a northwest-trending belt across southern Arizona.*

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.

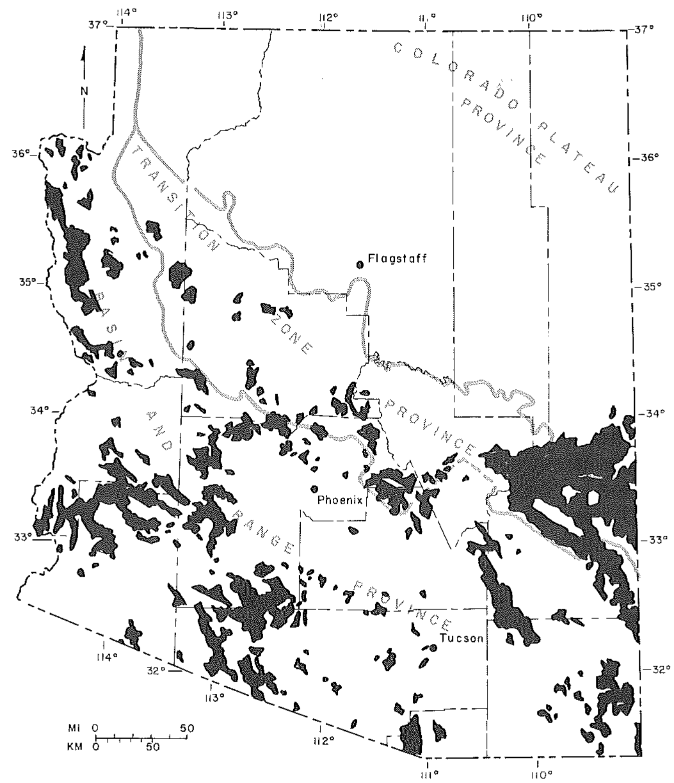
Arizona's fourth volcanic episode occurred during Late Cretaceous to early Tertiary time (85 to 45 m.y. ago), when volcanism and associated igneous activity migrated eastward back into Arizona and adjacent New Mexico. This eastward sweep of magmatism was due to a decrease in the dip or angle of the subducted 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

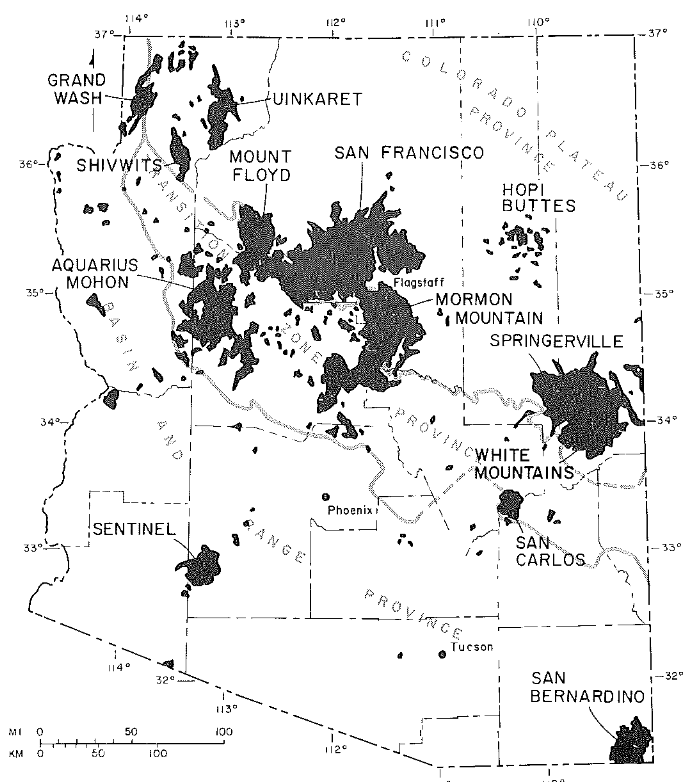
eroded volcanoes of the San Francisco Peaks and Mount Baldy in the White Mountains. The most recent basaltic volcanism, as indicated by the presence of preserved cinder cones, has been largely restricted to the San Francisco, Springerville, and Uinkaret volcanic fields of the Colorado Plateau and the 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

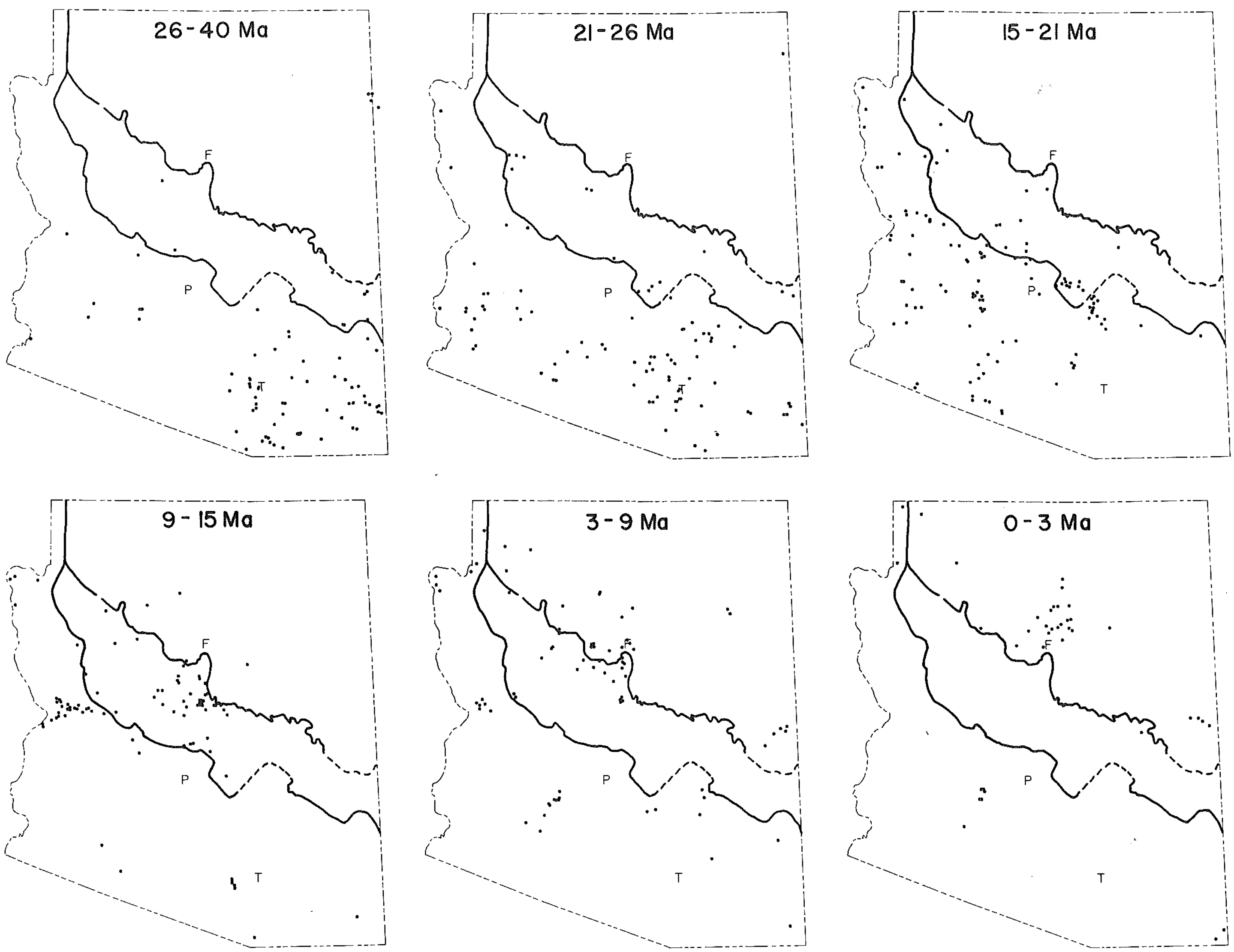


Figure 7. Distribution of isotopic age determinations on volcanic and related granitic rocks for different time periods during the last 40 m.y. These maps illustrate how volcanism migrated westward across Arizona between 40 and 15 Ma (million years ago) and then migrated northeastward toward the Colorado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

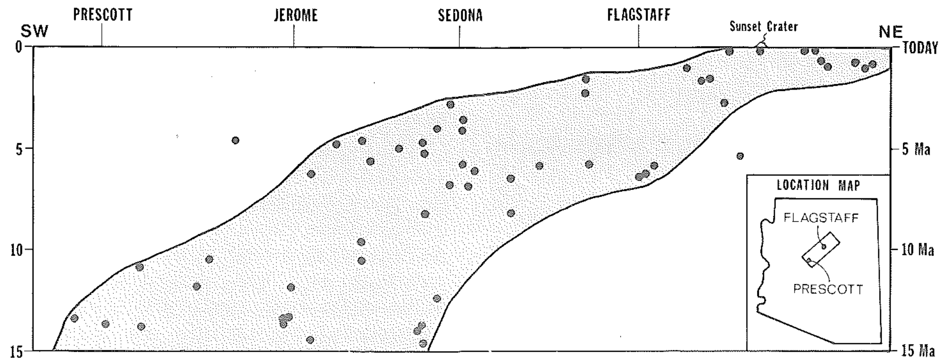


Figure 8. Diagram shows the ages of volcanic rocks versus their geographic positions along a northeast-southwest line through Prescott and Flagstaff. Volcanism migrated northeastward during the last 15 m.y. The most recent volcanism occurred slightly northeast of Flagstaff.

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.

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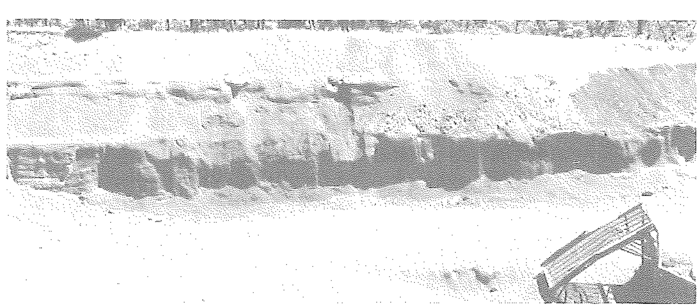

Figure 10. Layer of red cinders at the U.S. Forest Service Porter Mountain pit, northeast of Lakeside, Navajo County. The grate in the lower right is used to size the cinders before shipping. Photo by John W. Welty.