

Geologic History of Arizona

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The wonderful diversity of Arizona landscapes results from a very complex geologic history. The scenery was created from environments ranging from warm shallow seas to windy desert dunes and from violent volcanic eruptions to lazy lava flows. The many episodes of mountain building and the intrusion of igneous rocks deep in the crust with their accompanying veins of rich mineral deposits have created the abundance of mineral species found in Arizona.

1 Landscape Types

Two very different types of landscapes occur in Arizona: the Basin and Range Province of southwestern Arizona and the Colorado Plateau Province of northern Arizona, with a Transition zone between them (Figure 1). The present topographic differences between these provinces result in major contrasts in the distribution of population, agriculture, industry, water supply, and tourist attractions.

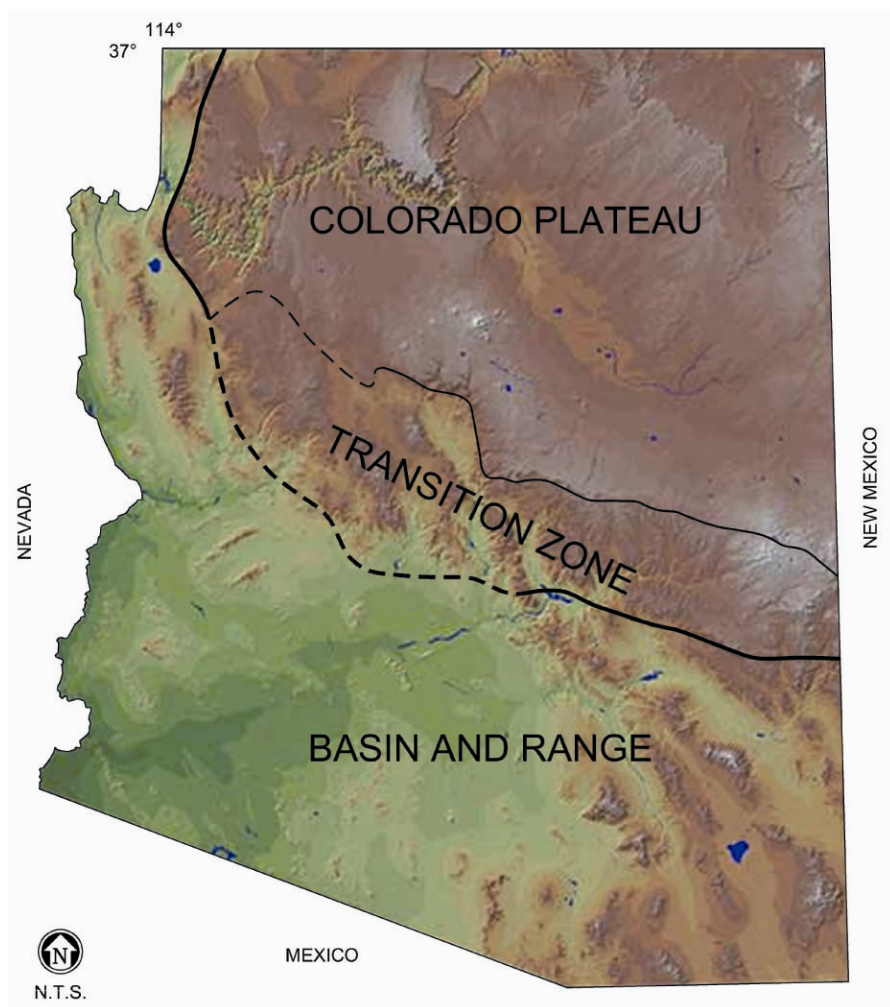


Figure 1. Map of physiographic provinces in Arizona.

Most people live in the Phoenix, Tucson, and Yuma metropolitan areas in the valleys of the Basin and Range Province. In these broad valleys, there is more groundwater available, more industry, and more agriculture. The “sky islands” that are the mountain ranges were originally likened to ‘worms crawling northwesterly out of Mexico’ because of their appearance on maps. Spectacularly collectible minerals occur in these mountains, mainly in the mines that extract the metals that were deposited during the various mountain building events. All of the large, open pit porphyry copper mines and other mines that yield Arizona’s metal production occur in the Basin and Range Province.

Most of the national parks and tourist attractions, such as the Grand Canyon, Petrified Forest, Sunset Crater, and Monument Valley, occur in the Colorado Plateau Province. Here, nearly flat sedimentary rock layers are cut by steep-walled canyons. These canyons allow water to drain out of the formations, making water a rare and precious resource in northern Arizona. Where these formations are eroded into mesas and buttes, the reddish sandstones make very photogenic scenery, such as in Monument Valley. All of the energy resources produced from Arizona, such as coal from Black Mesa, uranium from north of the Grand Canyon, and oil from the Navajo Reservation, are located in the Colorado Plateau Province. Most of this province is either national parks or national forests or Indian reservations.

The Transition Zone between the Basin and Range and the Colorado Plateau provinces has some of the characteristics of both adjacent provinces. It has flat-lying sedimentary rocks, such as at Sedona, but also has some mountainous areas, such as the Mogollon Rim, and many national forests.

Only 12 percent of Arizona is private land. Even in the Basin and Range Province, much of the desert area is Federal or State land, either bombing range, military bases, Indian Reservation, or national forests in the mountains.

This division of Arizona into the different physiographic provinces occurred relatively ‘late’ in Arizona’s geologic history. The Colorado Plateau was uplifted about 50 million years ago (Ma) and the Grand Canyon cut during the last 5 Ma.

The early geologic history (2,000 to 250 Ma) of the Basin and Range and Colorado Plateau provinces is very similar. But at the beginning of the Age of Dinosaurs (Mesozoic Era - about 250 Ma), the Earth’s tectonic plates reversed directions. Before that, during the Paleozoic Era (542-250 Ma), Arizona was on the trailing edge of a continent moving eastward. During that time, Arizona enjoyed a calm quiet environment of shallow seas and lazy rivers. In the Paleozoic, most of the mountain building activity occurred on the east coast of North America. Later, during the Mesozoic and Cenozoic Eras, Arizona was on the leading edge of the North American plate (Figure 2). The leading edge was a very exciting, but dangerous, place during those times, with lots of earthquakes, volcanic activity, and accompanying deposition of beautiful minerals. The physical environment was much like the present Cascade Mountains of the northwestern United States.

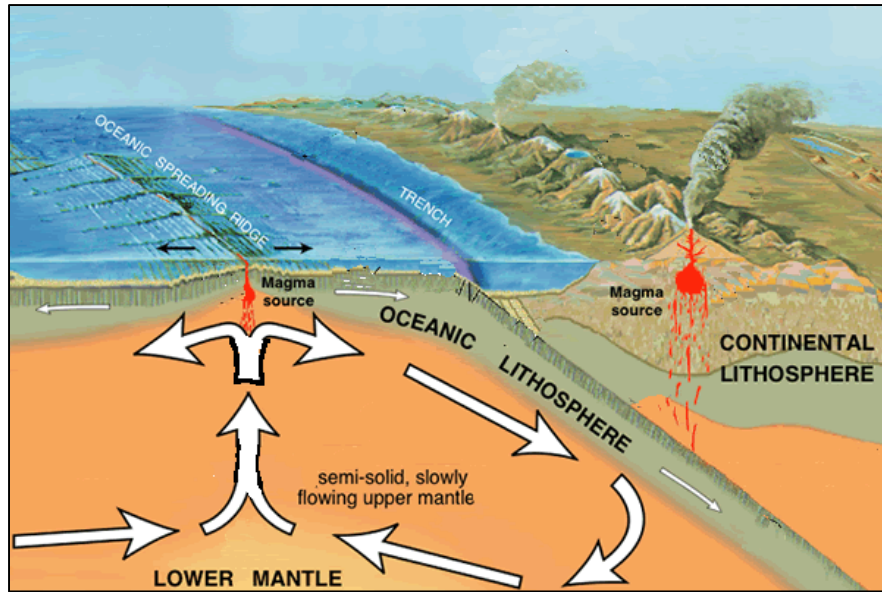


Figure 2. Cross section showing the plate tectonic setting of an oceanic plate being subducted eastward under a continental plate.

2 Geologic History

The mountain building episodes that brought mineralization to Arizona occurred mainly during the Precambrian and the Mesozoic and Cenozoic eras. Volcanic eruptions and intrusion of granitic rocks and minerals in the associated veins rose from the eastward-dipping oceanic plate that was being subducted under the northwestward advancing North American continent.

Almost every rock type and geologic age can be found in Arizona, especially in the Basin and Range Province. The geologic map (**Figure 3**) shows scraps of various rock types in the mountains, as they were cut up and faulted by the numerous mountain building episodes. The outcrops look like a jigsaw puzzle constructed with the added complication of the fourth dimension – geologic time. Many geologists have deciphered this complex geologic history so that a sequential geologic history can be summarized (Jenney and Reynolds 1989).

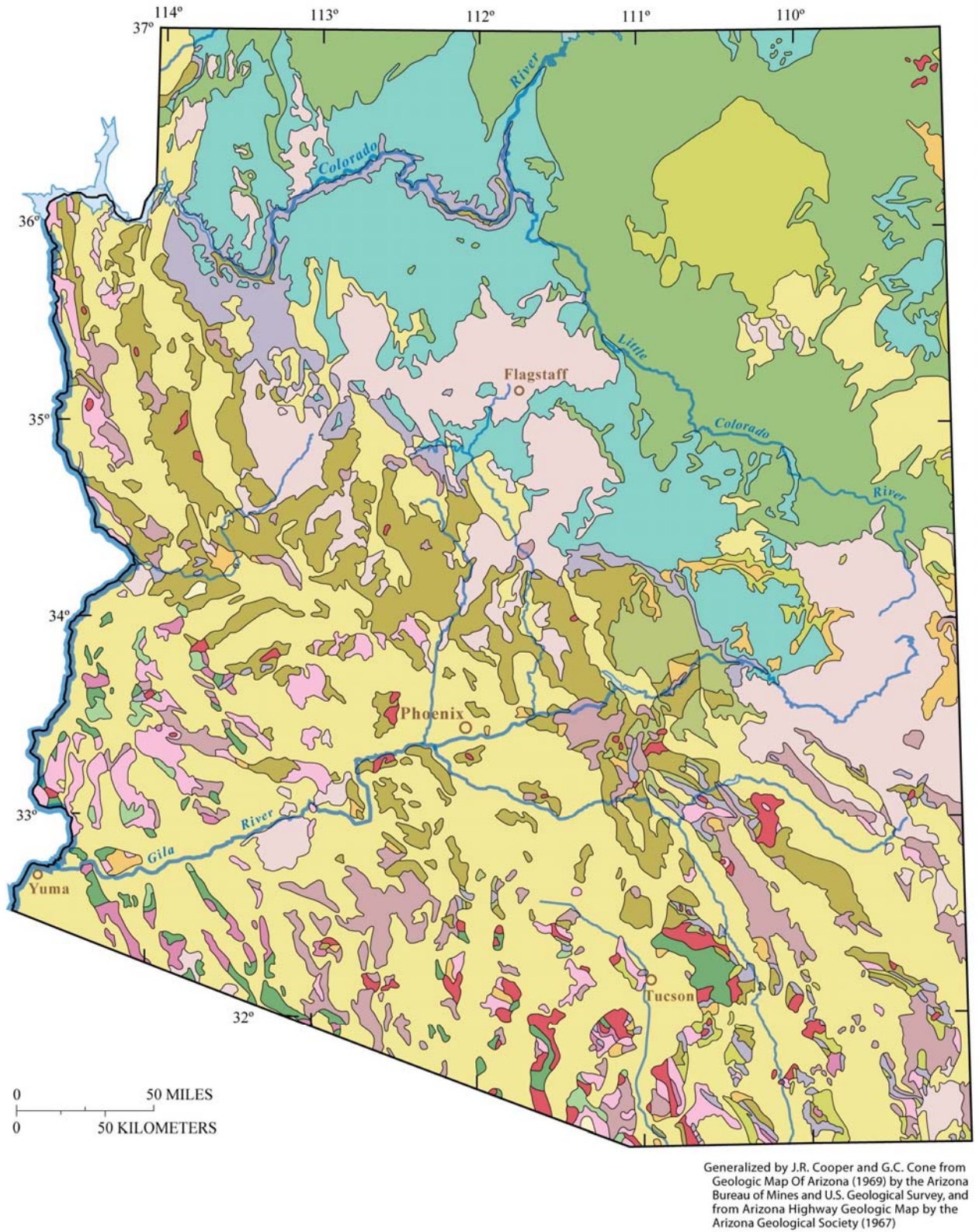


Figure 3a. Geological map of Arizona. Courtesy of John Callahan.

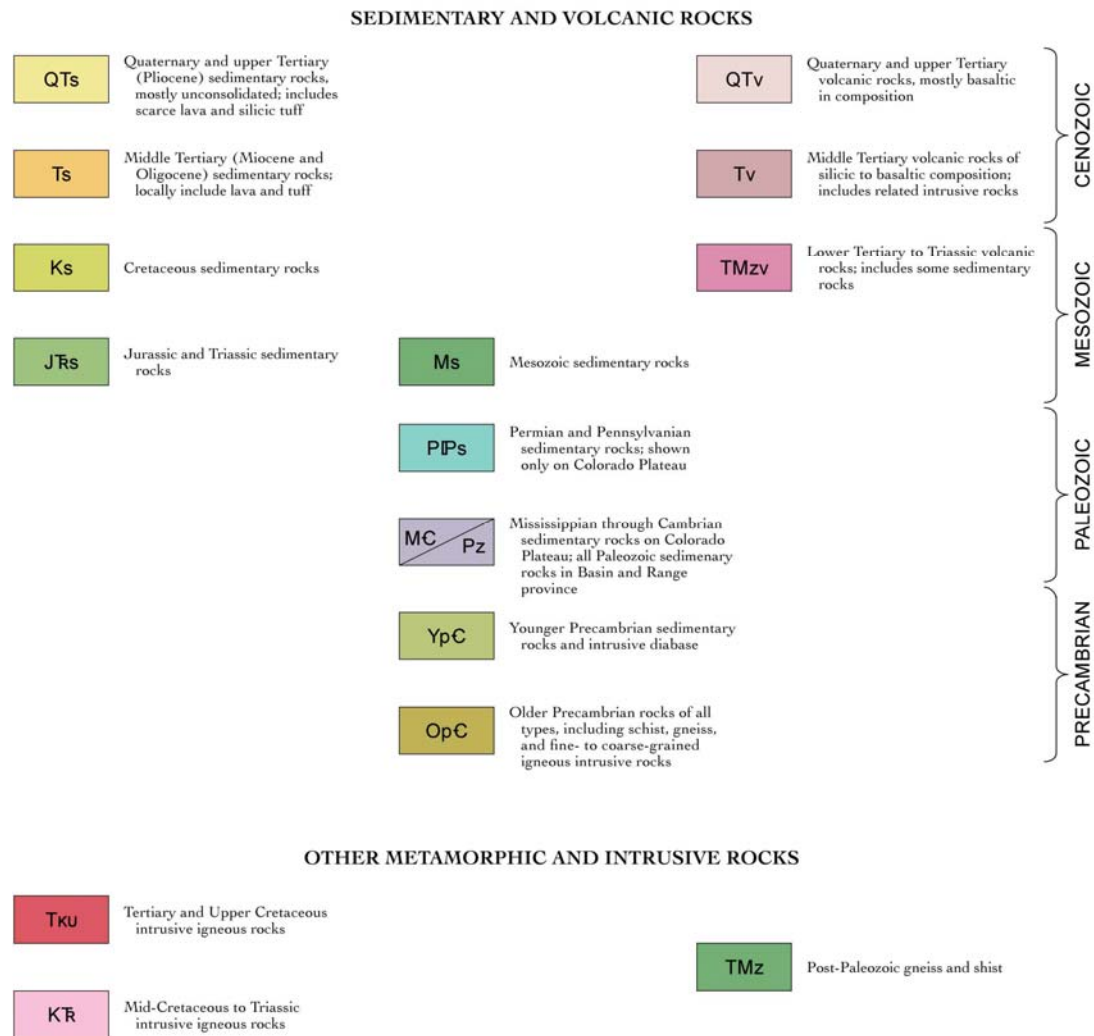


Figure 3b. Explanation of geological map of Arizona. Courtesy of John Callahan.

2.1 Late Precambrian – Proterozoic Eon (1,800 - 542 Ma)

During the Late Precambrian, which is called the Proterozoic Eon (1,800 – 542 Ma), Arizona was cooked, contorted, and squeezed by several major episodes of mountain building. The Yavapai, Vishnu, and Pinal schists have been through intense metamorphism, were intruded by granitic rocks, and were later buried by sedimentary rocks. These deformed rocks can be seen in the bottom of the Grand Canyon, in the Salt River Canyon, and in other mountain ranges around the state.

The oldest Precambrian rocks in northern Arizona, in the Prescott area and in the bottom of the Grand Canyon, were deposited and metamorphosed during the Yavapai episode of mountain building. These ancient rocks are 1,800 to 1,740 million years old (Ma). These rocks are a series of metamorphosed volcanic rocks (basalts and rhyolites) and associated sedimentary rocks. The volcanogenic massive copper and zinc sulfide ore deposits in Yavapai County (such as the Verde district at Jerome) were formed by submarine hot springs that precipitated the sulfides directly onto the sea floor, in an environment similar to the ‘black smokers’ observed on the deep seafloor today.

A later Proterozoic mountain building episode, the Mazatzal, was active in Arizona from about 1,700 to 1,615 Ma. The igneous rocks in the New River and Mazatzal Mountains were more quartz-rich than the earlier rocks. In southern Arizona, the Proterozoic rocks consist of the satiny, greenish-gray Pinal Schist. Throughout southeastern Arizona, the Pinal Schist was intruded by granite or granodiorite.

The earlier Precambrian metamorphic and igneous rocks were intruded by granites or pegmatites from about 1,450 to 1,400 Ma. These granites contain large one- to two-inch long, pink orthoclase crystals. The Oracle Granite of the Tucson area, the Ruin Granite in the Ray-Superior area, and the Zoroaster Granite in the bottom of the Grand Canyon are examples. Veins in these rocks produce exotic minerals containing beryllium, lithium, tantalum-niobium, bismuth, uranium, or tungsten. The powerful forces of this mountain building episode created faults and fractures in a structurally weak zone, called the Texas Zone, that trends west-northwest from Texas to California. These zones of weakness were frequently reopened during later mountain building episodes, allowing hot, mineral-bearing solutions the open space that was needed for the formation of vein minerals.

Sedimentary rocks were deposited in rift basins in the western U.S. during the Grenville mountain building episode from about 1,200 to 1,000 Ma, while the main mountain building was occurring in the eastern U.S. and Canada. The Keweenaw basalt flows and associated copper deposits of Michigan were deposited in these rift basins. Sedimentary rocks deep in the Grand Canyon and in central Arizona were deposited in similar basins in the interior of the North American continent. The Apache Group exposed in Salt River Canyon consists of shale and sandstone that were deposited in fluvial environments and of limestone that was deposited in a shallow sea. Some of the earliest fossils from Arizona are the stromatolites in this limestone that are the remains of mounds built by blue-green algae in warm, shallow seas. These are similar to stromatolites now forming in Shark Bay in Australia. These sedimentary rocks also include basalt or diabase that intruded the Apache Group at 1,050 to 1,140 Ma. The asbestos deposits in the Salt River Canyon were created by the metamorphism of the Mescal Limestone when the hot diabase intruded and baked the limestone into marble. Similar rocks, called the Unkar Group, occur in the Grand Canyon and include limestone, shale, quartzite, sandstone, and basalt dated at 1,070 Ma. In the Grand Canyon, these formations are overlain by sedimentary rocks called the Chuar Group and Sixtymile Formation that were deposited about 850 Ma.

The large gap in time between the Proterozoic granitic rocks and the Cambrian marine sediments is called the Great Unconformity (Figure 4). It represents a very long period of erosion in which Arizona was a continental area for about 900 million years. Sediments were deposited in a few down-faulted basins during this time, indicating an erosion period of about 350 million years in the Grand Canyon.

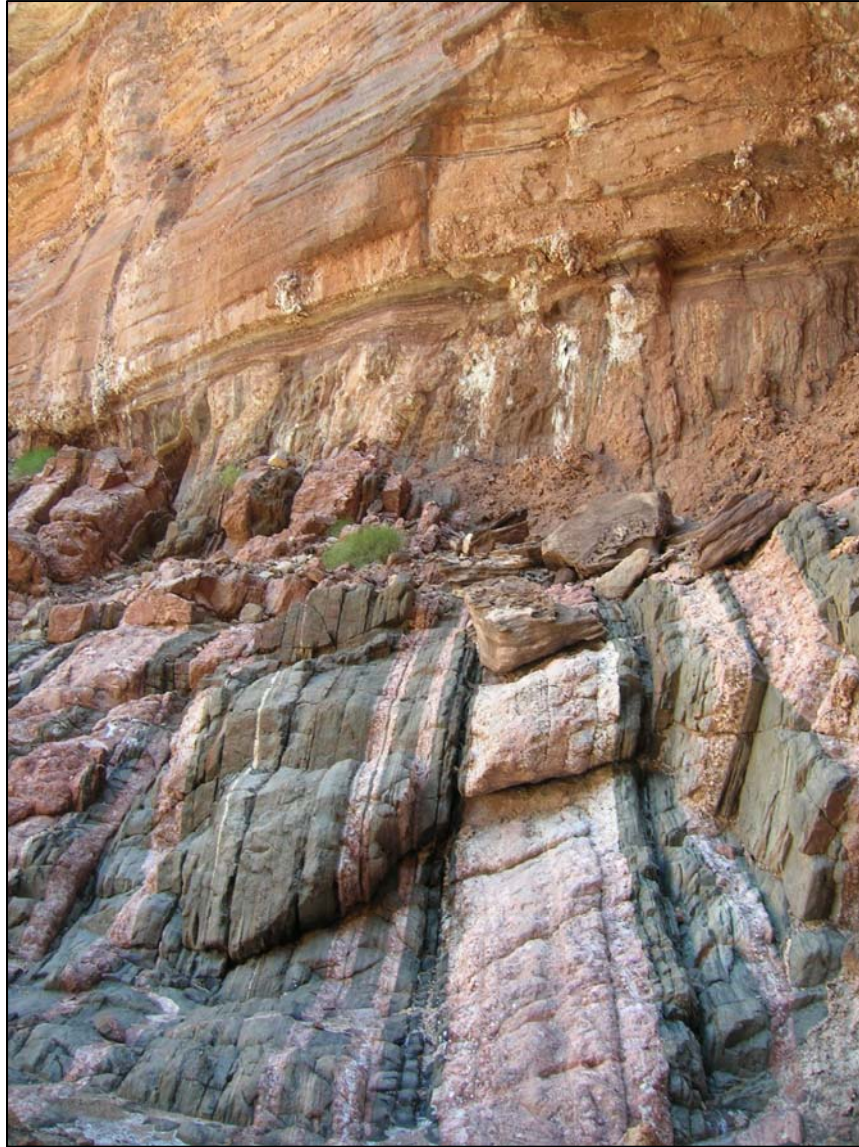


Figure 4. Great unconformity showing gap of 900 million years between Precambrian granite and Cambrian sedimentary rocks.

2.2 Paleozoic Passive Margin (542-251.5 Ma)

During the Paleozoic Era (542-251.5 Ma), Arizona was on the trailing edge of the North American continent, while the North American continent was moving eastward toward a collision with Europe and Africa. Therefore, Arizona did not experience any volcanic explosions or igneous intrusions during this long time period. However, during the three main orogenic episodes in the eastern U.S., Arizona received more continental sediments, mainly sandstones and siltstones. During the lulls between the mountain building episodes, warm shallow seaways extended across Arizona, creating thick sequences of limestone that now contain many beautiful caves. In the eastern U.S., the three main episodes with volcanism and metamorphism included the Taconic (490-445 Ma), Acadian (410-380 Ma), and Alleghenian (325-220 Ma) mountain building episodes. Because of the quiet shallow sea and lazy floodplain environments, abundant invertebrate fossils are preserved in the

Paleozoic rocks of Arizona (Bryant 1968). The limestones are important hosts to ore deposits and are the frequent deposition site of beautiful mineral specimens, such as wulfenite.

The shallow seaway expanded eastward across Arizona during the Middle Cambrian (520-488 Ma). This transgressing seaway deposited beach sands (~521-499 Ma). Overlying the sandstones, shale and siltstones were deposited in nearshore environments. These were, in turn, buried by marine limestones [~515-488 Ma]. These rocks are grayish olive-green to dark greenish gray limestone with worm borings and conspicuous thin beds of edgewise conglomerates. For the first time, fossils of invertebrates - trilobites, snails, brachiopods, and worm borings - show up in the sedimentary rocks.

In the Ordovician and Silurian Periods, the Taconic mountain building event (~488-444 Ma) created the ancestral Appalachian Mountains in the eastern U.S. This large continental assembly event caused Arizona to be above water and undergoing erosion during the most of the Ordovician and Silurian Periods, so that rocks of these ages are mostly missing in Arizona.

The eastward moving North American plate collided with Europe in the Acadian mountain building event (~410-380 Ma). During the Devonian Period, Arizona experienced frequent changes between marine and continental depositional environments. The scene was also complicated by a subduction zone and island volcanic arc system along the western coast of North America that was mainly active in Nevada. In southern Arizona, the Late Devonian Martin Formation, ~386-375 Ma, is typically dark gray to brownish black and consists of chert, limestone, sandstone, and shale. It contains primitive fish fossils in addition to the invertebrate fossils typical of the Cambrian formations.

During the Mississippian Period (359-318 Ma), there was a lull between the Acadian and the Alleghenian mountain building events. This lull allowed warm shallow seaways to engulf large areas of the western U.S. These seaways deposited massive thicknesses of limestone throughout the western U.S. The Mississippian limestones include Redwall Limestone of the Grand Canyon and the Escabrosa Limestone of southern Arizona, as well as the Madison Limestone in Wyoming. These Early Mississippian limestones, ~353-340 Ma, are cliff-formers and contain caves throughout Arizona, such as Kartchner Cavern in Cochise County or Vesey's Paradise in the Grand Canyon (**Figure 5**). Fossil crinoid fragments, corals, and brachiopods are abundant in these rocks.

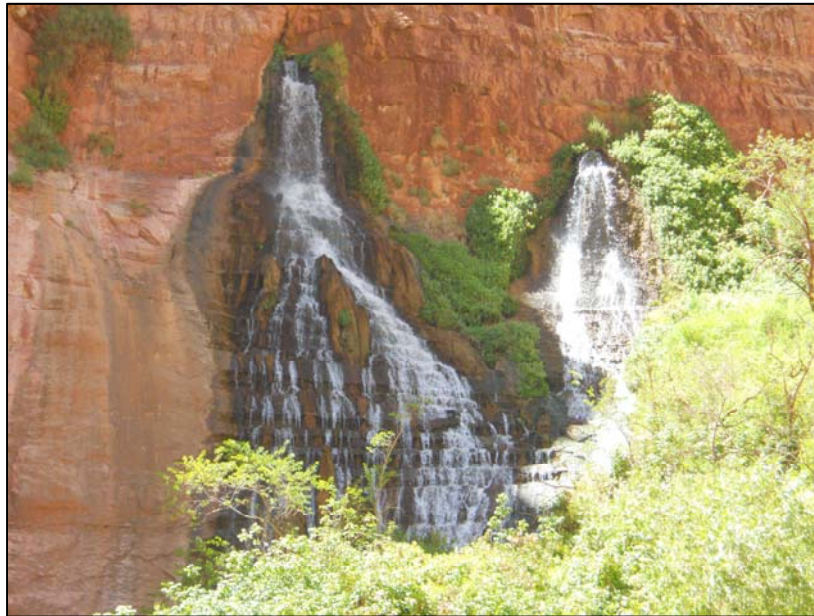


Figure 5. Water flowing from a cave in the Mississippian Redwall Limestone in the Grand Canyon.

The Alleghenian mountain building episode (320-220 Ma) was another major continental assembly event with all of the continents being massed together in a supercontinent known as Pangea. During the Pennsylvanian and Permian Periods (318-254 Ma), the collision of western Africa with the east coast of the U.S. created the Appalachian Mountains, which could have been as high as the Himalayas are now. Sea level in Arizona changed up and down as the glacial and interglacial stages on the southern continents waxed and waned. This created the ledge and slope topography typical of the Pennsylvanian formations in Arizona, as well as the coal measures in the mid-continent. Pennsylvanian and Permian formations in Arizona include alternating layers of gray and tan siltstone, sandstone, limestone, and dolomite and some spectacular red sandstones and shales at Sedona, Monument Valley, and the Grand Canyon. Some of the sandstones contain cross-beds that record the lee slope of sand dunes. The white cliff-forming Kaibab Limestone at the top of the Grand Canyon crops out at the surface of much of northern Arizona (Figure 6).



Figure 6. Paleozoic sedimentary rocks, aged 500 to 250 million years old, in the Grand Canyon.

When the major continental collision of North America, Europe, and Africa created the supercontinent Pangea and the Appalachian Mountains, the tectonic plates ground to a halt and eventually had to reorganize. As Pangea began to split, eastern North America separated from western Africa. The west coast of the U.S. then became the leading edge of the westward-moving North American continent. An east-dipping oceanic plate then began to dive under the North American plate and volcanoes spewed out all across southwestern Arizona and California. Deep in

these volcanoes and in the veins associated with the underlying granitic intrusions, the wonderful minerals common in Arizona were formed.

When the sea-floor spreading in the Pacific Ocean that drove the subducting oceanic plate under North America speeded up or slowed down, the slope of this subduction zone under western North America changed. When the dip of the subduction zone became shallower, the volcanism tapped a shallower level in the mantle. The shallower zone contained different suites of metals than deeper levels. As the dip of the subduction zone became shallower, the belts of magmatic activity moved eastward across California and Arizona. Thus, similar types of mineralization occur throughout the whole of southern Arizona, though formed at slightly different times. These pulses of volcanic and plutonic activity have been named different mountain building episodes, although they are all expressions of the westward-moving North American plate.

2.3 Triassic-Jurassic Mountain Building

Volcanic activity began in western Arizona at about 205 Ma as the first evidence of the Nevadan mountain building episode (205-145 Ma) in the Triassic and Jurassic Periods. In southeastern Arizona, granitic intrusions at 190 Ma brought mineral-rich veins and porphyry copper-gold ore deposits. Later oxidation and secondary enrichment created Bisbee's beautiful copper oxide minerals, azurite and malachite.

As volcanic activity began in southern Arizona, the area was uplifted and volcanoes spewed their ash far to the north. This volcanic ash was deposited in the Triassic-age Chinle Formation. The high amounts of silica in the ash allowed the petrification of the huge logs that had been washed down the river valleys from the high mountains in southern Arizona. This created the beautiful petrified wood in the Petrified Forest Member of the Chinle Formation (Figure 7).



Figure 7. Petrified wood in the Chinle Formation that formed about 200 million years ago.

Some dune sandstones are interbedded with volcanics in southern Arizona in the Santa Rita Mountains south of Tucson. These correlate with the Aztec or Navajo Sandstone of northern Arizona and of Zion National Park in Utah. A large coastal desert, similar to the modern Sahara desert, was present in the subtropical deserts of northern Arizona and Utah during the Jurassic Period.

2.4 Cretaceous Mountain Building

The volcanic activity of the Sevier mountain building episode (140-89 Ma) of Cretaceous age was located in California. Because the subduction zone was stable and did not flatten or move into Arizona, no vein-related minerals were formed in Arizona at that time. Instead, sand and clay were deposited in rivers and bays, and limestone was deposited in some shallow oceans. In southern Arizona, the sediments were deposited in a seaway that transgressed from the southeast, depositing a marine limestone with reefs made of clams in the Bisbee area. In northern Arizona, transgressing and regressing seaways from the mid-continent deposited sandstone and shale. These formations were deposited in coastal swampy environments that created Arizona's coal deposits.

Because the subduction zone became flatter throughout the Laramide mountain building episode (89-43 Ma), the volcanism and mineralization migrated eastward through geologic time. Thus, later magmatism and mineralization overprinted rocks deposited by the earlier pulses of mountain building (Keith and Wilt 1986).

The earliest phase of the Laramide mountain building episode in southern Arizona (85-80 Ma) is represented by small intrusions and volcanic centers. These igneous rocks are associated with porphyry copper-gold mineralization, such as the Copper Flat stock at Hillsboro in New Mexico and others in western Arizona.

Massive volcanic centers were built during the early Laramide phase (79-67 Ma) in southern Arizona. These large volcanoes explosively erupted large volumes of rhyolitic ash and andesitic volcanic rocks. Then the volcanic structure collapsed into the void left by the erupted ash leaving a huge caldera, such as the Cat Mountain Rhyolite west of Tucson (Figure 8). The lowest sedimentary rocks contain large exotic blocks ranging in size from cobbles to house-sized boulders of pre-existing rocks in a volcanic matrix. The ring and radial fractures created open space for the hydrothermal (hot-water) mineralizing solutions that deposited silver, lead, and zinc in veins. Examples of mining districts that produced excellent silver and lead minerals include those in the Santa Rita Mountains and Tombstone Hills.



Figure 8. Pink cliffs of Cat Mountain Rhyolite, formed as a volcanic ash flow about 74 million years ago in the Tucson Mountains.

Arizona is known as the Copper State because about two-thirds of the copper produced in the U.S. comes from Arizona each year. This copper is produced from the large porphyry copper deposits that were created during the middle Laramide mountain building phase (66-55 Ma) in the early Tertiary period. These disseminated copper deposits are associated with porphyritic (coarse crystals in a fine-grained ground mass) granitic intrusions (Keith and Wilt 1986). Examples of the Laramide porphyry copper deposits (Figure 9) include mines in the Tucson area: the Pima district (Twin Buttes, Sierrita-Esperanza, Rosemont, and Mission-Pima mines) south of Tucson, the Silver Bell mine northwest of Tucson, and the historic Ajo mine west of Tucson. The open pit copper mines also include mines in central Arizona: Ray, Miami, Pinto Valley, Carlota, Superior, and Resolution mines east of Phoenix; the Morenci and Safford mines of eastern Arizona; and the Bagdad and Mineral Park mines of northwestern Arizona. The porphyry copper systems are extremely large, covering most of any mountain range. These mining districts commonly have other types of deposits in a bulls-eye pattern outward from the copper-rich core in this sequence: copper-zinc, zinc-lead-silver-gold, and silver-manganese at the outer zones. Skarn deposits (contact metamorphic deposits with garnet and calcium silicate minerals) occur near the plutons. Oxidation and secondary enrichment have converted the primary copper mineral of chalcopyrite into richer copper secondary minerals of chalcocite, and the leachable 'copper oxide' minerals of azurite and malachite, and chrysocolla.



Figure 9. Aerial view of the porphyry copper deposit at the Ray mine north of Tucson, formed about 65 million years ago. Photo courtesy of ASARCO.

During the latest Laramide phase (54-43 Ma) in southern Arizona, granitic rock and pegmatites were intruded very deep (23 km) in the crust as a result of flat subduction of the down-going plate. Tungsten or quartz vein deposits are associated with garnet-muscovite granitoid stocks and pegmatite dikes. Many of these granitic plutons are near well-developed crushed zones. This flat subduction or underthrusting of the down-going plate toward the northeast under the Colorado Plateau thus raised the Colorado Plateau and areas further northeast to be eroded into an Eocene erosion surface. The Wilderness Granite in the Santa Catalina Mountains is an example of these igneous rocks (Figure 10) that were solidified as much as 14 miles under the surface.



Figure 10. White cliffs of Wilderness Granite, formed about 43 million years ago, in the west face of the Santa Catalina Mountains, Tucson.

2.5 Tertiary Mountain Building

During the mid-Tertiary mountain building episode (42-15 Ma), there were again massive volcanic centers that erupted large amounts of volcanic ash. The mountain ranges dominated by these ash flow tuffs and related volcanic flows include the Superstition, Galiuro, Chiricahua, and Tumacacori mountains, and many others in western Arizona. As the subducting slab became steeper and the magmatic arc moved from the east to the west, the types of ore deposits and chemistry and types of minerals of the associated volcanic and plutonic rocks changed (Keith and Wilt 1985).

The early sediments of the mid-Tertiary mountain building episode were deposited in local basins containing minor volcanics, local conglomerates and lacustrine deposits of carbonates and gypsum and clay, with minor uranium, secondary copper, and industrial mineral deposits.

The middle phase of the mid-Tertiary mountain building episode produced widespread volcanism and granitic stocks, such as the volcanic rocks in the Galiuro Mountains and Chiricahua Monument (Figure 11). An earlier minor phase contains gold-copper veins associated with dark-colored dike swarms. A later more extensive phase contains silver-lead-zinc skarns and replacements in contact zones of stocks and small batholiths that are associated with large volcanic caldera systems. Mining districts of this age include the Aravaipa, California, Castle Dome, Middle Pass, Swisshelm, and Ash Peak districts.



Figure 11. Outcrop of rhyolite, formed as volcanic ash about 26 million years ago, at Chiricahua National Monument.

The latest phase of the mid-Tertiary mountain building episode consists of coarse clastics and local volcanics and stocks that are deformed by low-angle, normal, detachment faults. Mineral resources consist of gold-silver veins and disseminations, such as the Oatman-Katherine district, and syngenetic stratabound uranium in lake beds and tuffs, such as the Anderson mine area in the Date Creek basin of western Arizona.

Arizona's present topography of mountains and valleys was created between 14-0 Ma as a result of the Basin and Range disturbance. When the subducting slab was cut off by the strike-slip movement on the San Andreas fault and transform boundary, the slab continued to descend without a driving force pushing it. Because part of the down-going slab was missing, the overlying slab foundered and parts of the overlying ground sank along steep normal faults. This collapse created the Basin and Range topographic province. This break-up allowed the intrusion of basalt from deep in the mantle, which is largely devoid of metal mineralization. However, useful industrial minerals (such as salt deposits under Phoenix, gypsum in the San Pedro and Verde valleys, clays, and zeolites in the Bowie area) were deposited in the basins. Some of the deep exotic blocks of peridotite that were brought up from the deep in the mantle by these basalt flows are found in the San Bernardino volcanic field of southeasternmost Arizona. Other recent volcanism (0-5 Ma) created the San Francisco volcanic field north of Flagstaff (Figure 12) and the Sentinel volcanic field west of Casa Grande.



Figure 12. Volcanic cones of black basalt in the San Francisco Peaks north of Flagstaff, formed between 5 to 0 million years ago.

3 Conclusion

After each mountain building episode, erosion tore the mountains down again. Gravity dictates: what goes up, must come down. It has been a continual cycle of building up into mountains and eroding down into sand and clay in river basins and ocean depths. The internal forces of plate tectonics and volcanism eventually yield to the surface forces of erosion. But the erosion into the roots of the mountains allows us to see into the former depths of the Earth where the beautiful crystals were formed. It is due to the mining of the rich ore deposits that beautiful specimens have been recovered and preserved. The ebb and flow of the oceans during the Paleozoic Era and the advance and retreat of the volcanism across Arizona during the Mesozoic and Cenozoic eras have created the wonderful richness of the mineral and fossil record in Arizona.

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