Formation of Arizona Minerals through Geologic Time

Jan C. Rasmussen, Ph.D., R.G.

Abstract

Numerous orogenic (mountain building) episodes generated mineralization when Arizona was on the leading edge of a continent. Arizona was subjected to volcanism and plutonism that rose from the plate that was being subducted under the westward-advancing North American continent. Deposition of minerals is associated with five orogenies (mountain building episodes) in the Proterozoic and five orogenies in the Mesozoic and Cenozoic. Three orogenies in the Paleozoic that affected the eastern United States influenced the deposition of sedimentary rocks in Arizona. The thirteen orogenies that affected deposition of collectible minerals and productive mining districts in Arizona are listed in Table 1.

The **Penokean (Hudsonian) orogeny (2000-1800 Ma** [million years ago]) and its correlative Mohave belt in Arizona added to the margins of the Archean (4000 to 2500 Ma) cratons (central cores of the continents). An Arizona example of the banded iron formations (BIF) may be the Pikes Peak iron formation in northern Maricopa County.

The **Yavapai orogeny (1800 – 1775 Ma**) includes the Prescott-Jerome belt that developed as an intraoceanic island arc from 1800 to 1740 Ma. Mining districts that may have formed during the Yavapai orogeny include the Big Bug (Iron King mine) and Verde (Jerome) districts. These mines are volcanogenic massive sulfide (VMS) deposits that were formed as black smokers exuded zinc, lead, and copper sulfides from undersea hot springs related to volcanism.

The **Mazatzal orogenic belt (1750 – 1600 Ma)** was added to the southern margin of the Yavapai belt between 1775 and 1600 Ma. In Arizona, granodiorite plutons and associated mineralization and later submarine volcanoes were accompanied by undersea hot springs (black smokers). These rocks were later subjected to high-grade regional metamorphism. In southern Arizona, metasedimentary and metavolcanic rocks of the Pinal Schist (1710 to 1675 Ma) were intruded by granodiorite (1675 to 1625 Ma) of the Mazatzal orogeny. Examples of zinc-copper volcanogenic massive sulfide deposits of the Mazatzal orogeny may include the Old Dick mining district (Bruce mine).

The **Oracle/Ruin "anorogenic" orogeny (1440 – 1335 Ma)** records the intrusion of peraluminous granites that are characterized by large potassium-feldspar (orthoclase) crystals. Examples may include the Tungstona mining district in Yavapai County, pegmatite deposits in the White Picacho district in Maricopa-Yavapai counties, and possibly the Four Peaks amethyst deposit.

The **Grenville orogeny (1200 – 900 Ma)** of the eastern United States and Canada is expressed in Arizona by rift basins of the Grand Canyon Supergroup and the Apache Group of central and southern Arizona. The diabase dikes that intruded the limestones contact metamorphosed them and created chrysotile asbestos veins.

After a long period of erosion, the Proterozoic rocks were buried beneath sandstones and quartzite of Cambrian age. During the Paleozoic, Arizona was on the trailing edge (passive margin) of the North American continent from 542-251.5 Ma. The plate tectonic regime during the Paleozoic involved the North American plate moving eastward over a westward-subducting plate in at least three main orogenies with active volcanism, magmatism, and metamorphism along the east coast of the U.S. These orogenies included the Taconic orogeny (490-445 Ma), the Acadian (or Caledonian) orogeny (410-380 Ma), and the Alleghenian (or Ouachita) orogeny (325-220 Ma). The effect of these orogenies on southern Arizona was in the nature of the

sediments being shed from continental areas in the east. During lulls in the mountain building activity, shallow seaways encroached on Arizona from the west or south, depositing limestone.

The **Taconic orogeny (490-380 Ma)** of eastern U.S., in Arizona was characterized by deposition of Cambrian sandstone, shale, and limestone in a shallow seaway that advanced eastward.

The **Acadian/ Caledonian orogeny (410-380 Ma)** of eastern U.S., in Arizona consisted of sandstones, siltstones, and marine carbonates of Devonian age. In the lull between the Acadian and Alleghenian orogenies, much of the North American continent was inundated by shallow seas. In the Mississippian in Arizona, thick sequences of limestone and dolomite were deposited throughout the state. These thick, cliff-forming Mississippian formations are the sites of most of the caves in Arizona. Beautiful speleothems of calcite are the collectible minerals later deposited in caves in these formations. The Redwall and Escabrosa limestones are also the source of much of the limestone that is mined for cement in Arizona at Clarkdale and Rillito, north of Tucson.

The **Alleghenian (Ouachita) orogeny (325 – 220 Ma)** in Arizona is recorded in Pennsylvanian, Permian, and earliest Triassic rocks of continental, marine, and mixed sedimentary environments. During this orogeny, the Appalachian Mountains were uplifted when the northwest coast of Africa impacted the eastern U.S. and the north coast of South America impacted the south coast of North America in the formation of the supercontinent Pangea. The alternation between thin ledges of limestone and slopes of siltstone/shale in Arizona Pennsylvanian formations may reflect the sea level changes caused by advances and retreats of glaciation in the southern hemisphere, where the continents were massed at the south pole as Gondwanaland. Sporadic uplift and subsidence of local arches and basins may also reflect the influence of upwarps and basins associated with ancestral Rocky Mountain tectonic activity. Along the Mogollon Rim in the Payson area at Promontory Butte, some of these formations are host to small uranium deposits.

In the Mesozoic and Cenozoic, active mountain building returned to Arizona. After the major continent-continent collision of North America, Europe, and Africa created the supercontinent Pangea and the Appalachian-Ouachita Mountains, the tectonic plates were forced to reorganize. In the Triassic, as Pangea began to split apart separating the eastern North American plate apart from Africa, the western coast of North America became the leading edge of the northwestward moving North American continent. The resulting subduction of the northeast-dipping Farallon oceanic plate under the North American plate caused volcanism and accompanying mineralization throughout the western U.S.

The **Nevadan orogeny (205-145 Ma) of Triassic-Jurassic age** in the southwestern U.S. is indicated by increasing amounts of volcanic ash (indicated by the weathering product of bentonitic clay) in Triassic and Jurassic formations of northern Arizona and by abundant volcanic and plutonic rocks in southern Arizona. During the early Mesozoic, higher areas in southern Arizona may have allowed alkaline solutions to travel through groundwater from the alkaline, uranium-rich plutonic and volcanic sources in southern Arizona through the Pennsylvanian-Permian sandstones and then deposit uranium in reduced environments of the collapsed cave formations of breccia pipes or organic-rich areas in roll-front uranium deposits of the Jurassic sandstone formations. Examples of breccia pipe deposits include the Orphan mine and Grandview mine exposed in the Grand Canyon. In latest Middle to Late Jurassic time, alkaline volcano-plutonic complexes formed in southern Arizona. In southeastern Arizona, plutonic rocks of metaluminous quartz alkalic magma chemistry are known from Bisbee (Warren mining district) and from the Courtland-Gleeson area (Turquoise mining district). Another metaluminous quartz alkalic magmatic suite occurs at Sugarloaf Peak in the Dome Rock Mountains of La Paz County western Arizona.

The **Cretaceous Sevier orogeny (140-89 Ma) of the Early Cretaceous** consisted of a stable (non-migrating and non-flattening) magmatic arc, with back arc basins located in Arizona, such as the Bisbee Group. A mid-Cretaceous shallow seaway transgressed from the southeast, depositing the Mural Limestone, which is a source of limestone for cement at Paul Spur east of Bisbee. Coal deposits formed in northern Arizona in the Black Mesa basin.

The **Laramide orogeny (85 – 43 Ma) (Late Cretaceous and Early Tertiary)** represents flattening subduction, in which the magmatic arc migrated eastward through geologic time. The Laramide orogeny has been subdivided into four phases: the earliest (Hillsboro), early (Tombstone), middle (Morenci), and late (Wilderness) phases.

The ***Late Cretaceous, Earliest Laramide (Hillsboro) phase (85-80 Ma) consists of copper gold mineralization*** related to metaluminous quartz alkalic magmatism, such as the Copper Flat stock at Hillsboro in New Mexico. Examples in western Arizona include the Mudersbach pluton in the central Plomosa Mountains and examples in southern Arizona include native copper in the high potassium andesitic volcanics at La Colorado south of Arivaca.

The Late Cretaceous, Early Laramide (Tombstone) phase (79-67 Ma) consists of lead-zinc-silver mineralization associated with caldera development of alkali-calcic volcanism and plutonism in southern Arizona. The Tombstone Assemblage is characterized by large volcanic centers (calderas) that experienced large volumes of explosive volcanism and ash deposits. Large exotic blocks in a volcanic matrix are generally interpreted as caldera infill or moat deposits from the collapse of the volcanic edifice. Examples include the Tucson Mountain Chaos, the Claflin Ranch Formation in the Silver Bell Mountains, the lower Salero Formation in the Santa Rita Mountains, and the Bronco Volcanics in the Tombstone Hills. Numerous areas in southern Arizona contain the roots of this caldera volcanism in the form of monzo-dioritic to quartz monzonitic plutons that are locally associated with lead-zinc-silver mineralization. Examples of Tombstone Assemblage plutons include the Josephine Canyon Diorite in the Santa Rita Mountains, the Schieffelin Granodiorite and Uncle Sam Tuff of the Tombstone Hills, and the Silver Bell Dacite in the Silver Bell Mountains. Examples of the metaluminous alkali-calcic districts with lead-zinc-silver mineralization include the Tombstone, Tyndall (Glove mine), Washington Camp, Patagonia (Duquesne-Washington group) and Salero mining districts.

The ***Early Tertiary, Middle Laramide (Morenci) phase (66-55 Ma) consists of porphyry copper mineralization*** associated with porphyritic stocks of quartz diorite to granodiorite composition of metaluminous calc-alkalic magma chemistry in southern Arizona. Mineralization of the Morenci Assemblage consists of the porphyry copper deposits that are the major source of historic copper production in Arizona. Examples include the Pima district (Twin Buttes, Sierrita-Esperanza, and Mission-Pima mines) south of Tucson and the Silver Bell mine northwest of Tucson. Other examples of porphyry copper deposits of the Middle Laramide include Ajo, Ray, Christmas, San Manuel, Mineral Park, Bagdad, Globe-Miami, Morenci, and Superior.

The ***Early Tertiary, Late Laramide (Wilderness) phase (54-43 Ma) consists of tungsten (W) mineralization*** associated with garnet-muscovite granitoid stocks and pegmatite dikes of peraluminous, magma chemistry. In the Little Dragoon Mountains, the main phase of the Texas Canyon pluton was intruded by the peraluminous calc-alkalic Adams Peak leucogranite. In the Huachuca Mountains, tungsten mineralization is probably related to the muscovite-bearing peraluminous alaskites that locally occur in southwest-directed thrust faults. An example of the Wilderness Assemblage mineralization is probably the Bluebird leucogranite in the Texas Canyon area. Peraluminous granites of Laramide age in Arizona include the peraluminous calcic magmatism of Las Guijas tungsten deposit and the peraluminous calc-alkalic magmatism associated with tungsten deposits at the Little Dragoon Mountains Bluebird deposit in Texas Canyon at approximately64 Ma, the Boriana tungsten deposit in western Arizona, and the mineralization in Oracle district associated with the Wilderness granite in the Santa Catalina Mountains. Additional possibilities in western Arizona for gold-rich, latest Laramide (Wilderness assemblage) ore deposits include the Vulture gold mine at approximately 75 Ma, the Copperstone gold deposit associated with southwest-directed thrust faults, and the Gold Basin deposit in Mohave County associated with 2-mica granites.

The **Galiuro Orogeny (43-13 Ma) of mid-Tertiary age** records the steepening of the subducting slab so that the central axis of the magmatic arc moved from the east to the west. The Galiuro orogeny is subdivided into early (Mineta), middle (South Mountain – calc-alkalic and later Datil – alkali-calcic), and late (Whipple) phases.

The ***Early Galiuro orogeny (Mineta phase) – 38-28 Ma*** records the deposition of sediments and volcanics in local basins, with minor volcanics, local conglomerates and lacustrine deposits of carbonates and gypsum and clay. Mineral deposits consisted of minor uranium in sedimentary and volcanic rocks, secondary exotic copper deposits, and industrial mineral deposits. Examples of exotic copper deposits near the porphyry copper deposits from which they were derived include the Copper Butte exotic copper deposit derived from the Ray porphyry copper deposit and the Ajo Cornelia exotic copper deposits derived from the Ajo porphyry copper deposit.

The two phases of the ***Middle Galiuro orogeny (South Mountain [30-22 Ma] and Datil [28-18 Ma])*** record widespread volcanism and emplacement of small stocks of calc-alkalic and later alkali-calcic magma chemistry. The earlier calc-alkalic phase (called the South Mountain phase) contains epithermal gold-copper veins associated with microdiorite dike swarms. Examples of the calc-alkalic phase include the deposits in the Little Harquahala district and the mines in the Kofa district. The later alkali-calcic phase (called the Datil phase) contains lead-zinc-silver skarns and replacement deposits in contact zones of stocks and small batholiths, associated with large caldera systems. Examples of the alkali-calcic phase include deposits of the Silver (Red Cloud mine), Castle Dome, Stanley, and Aravaipa mining districts.

The ***Late Galiuro orogeny (Whipple phase) – 189-13 Ma*** consists of coarse clastics and local volcanics and stocks of quartz-alkalic magma chemistry. These deposits are associated with microdiorite dikes and sometimes are associated with large, low-angle, normal, "detachment" faults, although the detachment faults are commonly reactivated along earlier thrust faults. Mineral resources of the Whipple phase consist of copper-gold-silver specularite replacement lenses, veins and disseminations in faults. Syngenetic stratabound uranium deposits were also deposited in lake beds and tuffs. The best known examples of these metaluminous quartz alkalic districts are the Oatman, Mammoth, Rowley, and Swansea gold districts. The oxidized zones of these deposits have produced a very unusual set of secondary minerals that are highly desirable for collectors.

The **San Andreas orogeny (Basin and Range Disturbance) - 13-0 Ma** produced the present physiography of the Basin and Range Province. The down-dropped fault basins are a result of the subducting Farallon slab being cut off by the strike-slip action on the San Andreas fault/transform boundary. As the underlying slab continued to descend and was missing in places, the overlying slab foundered and parts sank along steep normal faults creating the Basin and Range topographic province. This break-up allowed the intrusion of mantle basalt, which is largely devoid of mineralization, although some industrial minerals were deposited in the basins. Igneous rocks of this assemblage consist of basalt with local rhyolites, particularly where the normal faults allow mantle-derived basalt to ascend, as in the San Francisco volcanic field. The cinder cones near Flagstaff that are mined for cinders are an example of industrial minerals obtained from this assemblage. Other industrial minerals that were deposited in the down-dropped fault basins include salt in the Luke Salt basin in Glendale, the gypsum deposits in the San Pedro Valley and the Verde Valley, zeolites near Bowie, and sand and gravel deposits. The San Carlos basalts that contain olivine are an example of gemstones that are obtained from this assemblage.

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
San Andreas	Basin & Range	13-0	Latest Tertiary	anhydrous basaltic volcanism	Metalum. Alkalic	Sand, gravel, salt, zeolites, gypsum	San Francisco volcanic field, San Carlos olivine, Emerald Isle exotic Cu
Galiuro	Late (Whipple)	18-13	Late Tertiary	volcanics & local epizonal stocks	Metalum-inous Alkalic	Cu-Au-Ag in veins; epithermal Au-Ag veins	Oatman, Mammoth, Rowley,Swansea
	Middle (Datil)	28-18	Mid-Tertiary	alkali-calcic ignimbritic volcanics & plutons	Metalumin ous Alkali-calcic	Pb-Zn-Ag F veins, replace.; epithermal	Silver (Red Cloud), Castle Dome, Stanley, Aravaipa
	Early (South Mountain	30-22	Mid-Tertiary	calc-alkalic volcanics & plutons	Metalum. Calc-alkalic	Au +/- Cu-W veins & disseminated	Little Harquahala, Kofa
	Earliest (Mineta)	38-28	Mid-Tertiary	mostly within 'volcanic gap"	-	Uranium, clay, exotic copper	Ajo Cornelia, Copper Butte (from Ray)
Laramide	Late (Wilderne ss)	55-43	Early Tertiary	2-mica, garnet-muscovite granitic stocks, sills, dikes	Peralum. Calcic, Calc-alkalic	Au dissem. & qtz veins; W veins,	Oracle (Wilderness granite), Boriana, Las Guijas, Gold Basin, Copperstone
	Middle (Morenci)	65-55	Cretaceous-Tertiary	granodiorite - quartz monzonite porphyry stocks, NE to ENE-striking dike swarms	Metalumin ous Calc-alkalic	large disseminated porphyry Cu systems, local skarns & veins, fringing Zn-Pb-Ag	Ajo, Ray, Christmas, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci, Superior
	Early (Tombsto ne)	85-65	Late Cretaceous	qtz. monz. porph. stocks; ash flows	Metalum. Alkali-calcic	Pb-Zn-Ag veins & replacement deposits	Tombstone, Tyndall (Glove), Washington Camp, Salero
	Earliest (Hillsboro)	89-85	mid-Cretaceous	Volcanics, small stocks	Metalum. Alkalic	Cu-Au hydrothermal	Hillsboro, NM
Sevier		145-89	mid-Cretaceous			Sedimentary rocks	Bisbee Group sediments
Nevadan	Late	160-145	Late Jurassic	volcanics			
	Middle	205-160	Late & Middle Jurassic	Canelo Hills volcanics; plutonic rocks	Metalum. Alkalic	porphyry Cu-Au at Bisbee, Gleeson	Warren (Bisbee mine), Turquoise (Courtland-Gleeson)
	Early	230-205	Late Triassic	Fluid flow thru sedimentary rocks	Metalum. Alkalic	Uranium, vanadium, copper	Orphan, Grandview, Monument Valley
Alleghenian (Ouachita)		325-220	Miss. – Triassic	None	-	U in sed. rocks	Payson uranium
Acadian/ Caledonian		410-380	Devonian	None	-	Limestone	
Taconic.		490-445	Cambrian – Ord.	None	-		
Grenville		1200-900	Late Middle Proterozoic – Early Late Proterozoic	basalt flows, diabase dikes	Metalum. Alkalic	Serpentine asbestos	Sierra Ancha uranium Chrysotile (Salt R. Canyon)
"Oracle/Ruin"		1440-1335	Middle Proterozoic	K-feldspar megacrystic or porphyritic granites	Peralum. Calc-alkalic, Alkali-calcic	Pegmatites & greisens – Be, Li, Ta-Nb, U & W	White Picacho, Tungstona, Four Peaks
Mazatzal		1750-1600	Late Early Proterozoic	Basalt & rhyolite metavolc., schist	Metalum. Calcic	Cu-Zn-Ag VMS	Old Dick (Bruce)
Yavapai		1800-1775	Late Early Proterozoic	Andesite, schist, metarhyolite	Metalum. Calcic	Cu-Zn-Au VMS, Cu-Zn-Ag	Big Bug (Iron King), Verde (Jerome)
Penokean/ Hudsonian		2000-1800	Middle Late Proterozoic	Schist, banded cherty iron formation	Metalum. Calcic	BIF (Banded iron formation)	Pikes Peak iron

Table 1. Mountain building episodes in Arizona