Formation of Arizona Minerals through Geologic Time

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The formation of Arizona minerals through geologic time can be understood in the context of the plate tectonic setting of the southwestern United States. 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.

The ages of mineralization in Arizona range from Proterozoic (Late Precambrian - 2000 Ma [million years ago]) to Tertiary (2 Ma). 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.

1 Precambrian (1,800 - 542 Ma)

The Proterozoic (Late Precambrian) rocks exposed in Arizona are highly complex. In general, they consist of the Yavapai, Vishnu, or Pinal Schist and granodiorite intrusive rocks, intruded by granite. The Precambrian rocks are unconformably overlain by sedimentary units of Late Precambrian and Paleozoic age.

1.1 Penokean (Hudsonian) Orogeny (2000-1800 Ma)

Mountain building belts added to the margins of the Archean (4000 to 2500 Ma) cratons (central cores of the continents). The Trans-Hudson orogen in Canada records a sequence of rifting, opening of an oceanic basin, and subsequent closure along a subduction zone. The Penokean and Mohave are similar belts in the northeastern and southwestern U.S.

Banded iron formations (BIF) are common in the Early Proterozoic. The Superior type of BIF consists of thinly laminated rocks of the silica (chert) and iron oxide (hematite and magnetite), with iron silicate, iron carbonate, and iron sulfide. BIF are associated with chert, dolomite, quartzite, black carbon-bearing shale, and volcanic rocks. The Pikes Peak iron formation in northern Maricopa County may be an example of this orogeny in Arizona. This deposit is composed of numerous parallel lenses of banded cherty iron formation in metamorphosed rhyolite and diorite (Lindberg, 1989).

1.2 Yavapai Orogeny (1800 – 1775 Ma)

The Yavapai belt was added to the southern margin of the Wyoming craton between 1800 and 1775 Ma (Wicander and Monroe, 2000), as shown on Figure 1. The Prescott-Jerome belt developed as an intraoceanic island arc from 1800 to 1740 Ma above a subduction zone dipping southeast (Anderson, 1989).

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 Iron King ore contained delicate mineralogic banding of pyrite, sphalerite, and lenses of quartz-ankerite. Tiny grains of galena were assumed to contain silver and the gold was inferred to be contained in the pyrite (Lindberg, 1989).

The mines of the Verde district near Jerome produced most of the Precambrian ores of the southwestern U.S. Age dating of the rhyolite host Ash Creek Group of the Yavapai series indicated an age of 1790 Ma (Lindberg, 1989). The volcanogenic hot spring system produced massive sulfide ores with high copper and adjacent siliceous gold zones without copper. Hydrothermal solutions flowed through the fractured substrate of the Cleopatra extrusive rocks and vented onto the sea floor as hot springs which precipitated the massive sulfide deposits. Later deformation created major north-northwest trending folds (Lindberg, 1989).

1.3 Mazatzal Orogeny (1750 – 1600 Ma)

The Mazatzal belt was added to the southern margin of the Yavapai belt between 1775 and 1600 Ma (Wicander and Monroe, 2000) as shown on Figure 1. A major change in plate motions from1750 to 1740 Ma caused subduction in Arizona to flip and dip northwest under the Wyoming Archean craton, with accompanying granodiorite plutons and associated mineralization (Anderson, 1989). Later submarine volcanoes were accompanied by undersea hot springs (black smokers). The mountain building was complicated by later high-grade regional metamorphism.

In southern Arizona, sediments were shed into basins accompanied by felsic volcanism. These sedimentary and volcanic rocks were later metamorphosed into the Pinal Schist, which is generally a fine-grained, greenish-gray phyllite. The Pinal Schist in southern Arizona consists of a thick section (8,200 to 20,000 ft) of graywacke–slate sequences containing graded bedding, abundant volcanic debris, and intercalated volcanic flows (Cooper and Silver, 1964). The Pinal Schist in the Little Dragoon Mountains was dated at 1,695 ± 15 Ma (Silver, 1967). This is consistent with the regional age range of the Pinal Schist in southern Arizona from approximately 1,710 to 1,675 Ma (Silver, 1978).

The Pinal Schist (approximately 1,700 Ma) was intruded by granodiorite of the Mazatzal orogeny, which was active in southern and central Arizona between 1,675 and 1,625 Ma (Conway and Silver, 1989). In the Johnny Lyon Hills, the Pinal Schist was intruded by the Johnny Lyon Granodiorite, which was dated at 1,625 ± 10 Ma (Silver, 1978).

Examples of zinc-copper volcanogenic massive sulfide deposits may include the Old Dick mining district (Bruce mine). Lead isotope ages on galena from the Old Dick mine gave an age of 1700 Ma and from a Bruce mine gave an age of 1740 Ma. The mines produced approximately 1.7 million short tons of ore grading 12 percent zinc and 3.47 percent copper. The Old Dick and Bruce massive sulfide orebodies are located at the top of the Bridle formation os basaltic flows, pillow lavas and felsic volcaniclastic rocks. The Bruce deposit contains chalcopyrite, sphalerite, and galena, with minor amounts of associated arsenopyrite, pyrrhotite, cubanite, and mackinawite, with pyrite gangue (Lindberg, 1989).

1.4 Oracle/Ruin "Anorogenic" Orogeny (1440 – 1335 Ma)

The earlier Proterozoic rocks of Arizona were intruded by granites that are usually described as "anorogenic" (Anderson, 1989). These granites are characterized by large potassium-feldspar (orthoclase) crystals. However, it is more likely that these granites were the result of flat subduction along a large expanse of North America (Swan and Keith, 1986). The Tungsten King Granite in the Little Dragoon Mountains was dated at 1,420 ± 10 Ma (Silver, 1978). Other examples are the Oracle Granite in the Santa Catalina Mountains and the Ruin Granite of the Schultze and Ray mining districts. The Tungstona mining district in Yavapai County produced more than 7,500 short ton units of tungsten ore as WO_3. The chief ore mineral is wolframite, with some disseminated scheelite and a small amount of beryl (Lindberg, 1989).

Pegmatite deposits in Arizona include the White Picacho district in Maricopa-Yavapai counties. The pegmatites occur within igneous and metamorphic rocks of Precambrian age and show as irregular white bodies in darker host rocks (Lindberg, 1989). The most abundant pegmatite contains mineralogically simple assemblages of quartz, potash feldspar, and lesser amounts of sodic plagioclase and muscovite with accessory minerals of garnet, biotite, beryl, and black tourmaline. The second type is similar, but contains additional accessory minerals and is more coarsely crystalline. The third type of pegmatite contains lithium-bearing minerals with quartz, potash feldspar, spodumene, amblygonite, and other lithium-bearing phosphate minerals, Lepidolite, and pink and green tourmaline (Jahns, 1952). Another possible example of the mining districts of this age is the Four Peaks amethyst deposit (Keith and others, 1983).

1.5 Grenville Orogeny (1200 – 900 Ma)

The Grenville orogeny in the eastern United States and Canada consists of sandstones, shales, and carbonates that were highly deformed, metamorphosed, and intruded by various igneous bodies (Wicander and Monroe, 2000). During this time period, a midcontinent rift developed from Lake Superior southwestward to Kansas. Rift zones accumulated Keweenawan rocks of clean quartz sandstones and conglomerates and basaltic lava flows that contain native copper.

Examples in Arizona of the Keweenawan type rocks include the Grand Canyon Supergroup and associated formations (Elston, 1989) and the Apache Group of central and southern Arizona (Wrucke, 1989). Both assemblages contain basal conglomerates, sandstones (quartzites), shales, limestones, and basalt flows with associated dikes and sills of diabase. These formations are located in down-faulted troughs.

Apache Group rocks crop out in many mountain ranges in southeastern Arizona. In the Little Dragoon Mountains, the diabase that intruded the Apache Group was dated at 1,100 ± 15 Ma (Silver, 1978). The Sierra Ancha diabase sill was dated at 1,140 ± 40 Ma by K-Ar (Damon and others, 1962) and a sill near Miami was dated at 1040 ± 30 Ma (Banks and others, 1972) (Wrucke, 1989).

Apache Group rocks crop out in Salt River Canyon, where the intrusion of diabase cut across karst horizons within the Mescal Limestone. Metamorphic reactions between chert that had been deposited within karst horizons and the dolomitic host rocks formed thin tabular bodies of calcium magnesium silicate minerals (serpentine). The chrysotile asbestos veins are up to 2 inches wide within a serpentine envelope up to 1.5 feet thick. Most of the asbestos deposits are located within 25 feet of the upper or lower contact of a diabase sill where it cuts across the stratigraphy (Lindberg, 1989). Some minor uranium deposits were emplaced into the hydrocarbon-bearing siltstone member of the Dripping Spring Quartzite within the Apache Group in the Sierra Ancha area of Gila County (Lindberg, 1989).

After a long period of erosion, the Proterozoic rocks (Pinal Schist, Precambrian granitic rocks, and Proterozoic sedimentary rocks) were buried beneath sandstones and quartzite of Cambrian age.

2 Paleozoic Passive Margin (542-251.5 Ma)

Arizona was on the trailing edge of the eastward-moving North American continent during the Paleozoic. Therefore, Arizona experienced passive margin or miogeoclinal sedimentation of sandstone, shale, and limestone. 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 along the east coast. These included the Taconic orogeny (490-445 Ma), the Acadian (or Caledonian) orogeny (410-380 Ma), and the Alleghenian (or Ouachita) orogeny (325-220 Ma) (Janke, 2010).

The principal 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, which resulted in the deposition of limestone. Characteristics of Paleozoic formations in southeastern Arizona are summarized in Bryant (1968).

The Paleozoic limestones were generally reactive to hydrothermal solutions, so hydrothermal solutions generated by later orogenic episodes were influenced to deposit metallic mineralization in these limestones. Throughout southern Arizona, the lower Paleozoic formations generally contain the richer primary copper sulfide mineralization.

2.1 Taconic Orogeny (490-380 Ma)

Cambrian rocks in Arizona consist of a transgressive sequence of sandstone from beach deposits, overlain by shale, and then limestone as the shallow sea advanced over the land and previous deposit. In northern Arizona, the Cambrian formations consist of the Tonto Group of Tapeats Sandstone, Bright Angel Shale, and Muav Limestone. In southern Arizona, the similar sequence consists of the Bolsa Quartzite and Abrigo Formation.

The Tapeats Sandstone is Early Cambrian in the western Grand Canyon and Middle Cambrian in the eastern areas. It is medium- to coarse-grained feldspathic quartz sandstone. The Bright Angel Shale, consisting of sandstone, siltstone, and shale with glauconitic grains and hematitic ooids, also becomes younger to the east. The Muav Limestone is Middle Cambrian in the western canyon and is late Middle Cambrian in the eastern areas. It consists of dolomitic packstone and mudstone and nodular limestone (Middleton, 1989).

In southern Arizona, the Bolsa Quartzite (Middle Cambrian [~521-499 Ma]) is pale orange on a fresh surface to light brown on a weathered surface. It unconformably overlies the Pinal Schist and the Precambrian granitic rock. The major part of the unit consists of thick- to very thick-bedded, medium- to very coarse-grained, slightly cross-bedded quartzite. The Abrigo Formation (Middle to Upper Cambrian [~515-488 Ma]) is notable for its grayish olive-green to dark greenish gray limestone with worm borings and conspicuous thin beds of conglomerates.

2.2 Acadian/ Caledonian Orogeny (410-380 Ma)

In Arizona, Devonian rocks record deposition during two major transgressive-regressive episodes in Late Devonian time (Beus, 1989). Devonian rocks are predominantly marine carbonates, but also contain clastic sediments. The earlier complex is mainly early Late Devonian (Frasnian) in age and includes the Temple Butte, Elbert, and Aneth formations in northern Arizona and the Martin Formation and lower parts of the Morenci, Portal, and Swisshelm formations in central and southern Arizona.

The upper complex is of latest Devonian (late Famennian) age and includes the Pinyon Peak Limestone and Ouray Formation in northwestern and northeastern Arizona and all of the Percha and upper Morenci, Portal and Swisshelm formations in southeastern Arizona (Beus, 1989). The Martin Formation (Late Devonian [~386-375 Ma]) overlies the Cambrian formations in southern Arizona. The rocks are typically dark gray to brownish black and consist of chert, limestone, sandstone, and shale.

In the lull between the Acadian and Alleghenian orogenies, much of the North American continent was inundated by shallow seas. In Arizona, thick sequences of limestone and dolomite were deposited throughout the state (Beus, 1989). The Escabrosa and Redwall Limestones (Early Mississippian [~353-340 Ma]) are massive cliff-formers. Fossil crinoid fragments, corals, and brachiopods are abundant.

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 are also the source of much of the limestone that is mined for cement in Arizona at Clarkdale and Rillito, north of Tucson.

2.3 Alleghenian (Ouachita) Orogeny (325 – 220 Ma)

In Arizona, Pennsylvanian and Permian rocks record environments of continental, marine, and mixed sedimentary environments (Blakey and Knepp, 1989). These variations reflect the orogenic pulses in the orogenic belt of the eastern and southern United States. 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 (Levin, 1997).

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.

The Naco Group (Pennsylvanian - Permian) in southern Arizona consists of the Horquilla Limestone, Earp Formation, Colina Limestone, Epitaph Dolomite, Scherrer Formation, Concha Limestone and Rain Valley Formation (Gilluly and others, 1954). In northern Arizona, the Pennsylvanian and Permian formations consist of the Supai Group, Hermit Formation, Coconino Sandstone, and Toroweap and Kaibab formations.

The Lower and Middle Triassic Moenkopi Formation, consisting mainly of redbeds, formed on a gently westward-sloping plain adjacent to and periodically flooded by a shallow sea (Blakey, 1989). The overlying Chinle Formation consists of coarse- to fine-grained sandstones and variegated siltstones and shales in a continental setting with some ash beds. This change reflects a major change in the geologic setting from a passive margin to the initial stages of mountain building in Nevada and southern Arizona.

Along the Mogollon Rim in the Payson area at Promontory Butte, some of these formations are host to small uranium deposits. The solutions that carried the uranium may have been younger. Uranium lea dates on uraninite in uranium breccia pipes have returned U-Pb age dates of both 260 Ma (Late Permian) and 200 Ma (Late Triassic- Early Jurassic (Ludwig and Simmons, 1992).

3 Mesozoic - Cenozoic Mountain Building

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.

3.1 Nevadan Orogeny (205-145 Ma) – Triassic-Jurassic

The initiation of the western continental margin in the southwestern U.S. in Late Triassic time is indicated by increasing amounts of volcanic ash (indicated by the weathering product of bentonitic clay) in the Chinle Formation. The gentle uplift to the south or southwest of the Chinle outcrops (Blakey, 1989) may indicate an early effect of the magmatic arc in southern Arizona that would have been enhanced by increasing uplift in the Jurassic during growth of the magmatic arc.

This northward tilt from the 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 (Wenrich, 1989). The uranium could then be deposited 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 (Wenrich, 1985) include the Orphan mine and Grandview mine exposed in the Grand Canyon. Uranium sandstone deposits of the Colorado Plateau in Arizona include the uranium deposits in the Triassic Chinle Formation and Jurassic sandstones of the Morrison Formation and other areas in Monument Valley (Keith, 1970).

The first sedimentary and volcanic rocks of the Jurassic Nevadan orogeny were deposited in western Arizona at approximately 205 Ma (Tosdal and others, 1989). By the Early Jurassic (~220 Ma) rhyodacitic ash-flow tuffs, flows, and volcaniclastic rocks formed an extensive volcanic field in southern Arizona. Interbedded with these volcanic rocks are quartz sandstones correlative with the Navajo Sandstone of northern Arizona.

In latest Middle to Late Jurassic time, alkaline volcano-plutonic complexes formed in southern Arizona. In southeastern Arizona, plutonic rocks of quartz alkalic magma chemistry are known from Bisbee (Warren mining district) and from the Courtland-Gleeson area (Turquoise mining district) (Keith and others, 1983).

The porphyry copper-gold mineralization at Bisbee is associated with the Sacramento stock, dated at approximately 190 Ma with magma chemistry that is metaluminous quartz alkalic. The Juniper Flat granite north of Bisbee was emplaced at 171 ± 7 Ma (Marvin and others, 1973) or 182 ± 2 Ma (Creasey and Kistler, 1962) with magma chemistry that is more silver- and lead-rich and copper-gold poor than the porphyry copper-gold mines at Bisbee.

The Turquoise district in Cochise County includes the Defiance, Gleeson, and Silver Bill mines that have produced beautiful wulfenite specimens. The Gleeson Quartz Monzonite in the Dragoon Mountains was also emplaced at about 185 Ma (185 ± 4 Ma by Marvin and Cole, 1978; or 183 ± 5 Ma by Marvin and others, 1973, 1978). The magma chemistry may be metaluminous quartz alkalic (Keith, personal communication, 2013; Keith, 2000, 2002). Mines in the Courtland-Gleeson area are primarily lead-zinc silver oxidized replacement orebodies in fault fissures in Upper Paleozoic limestones (Keith, 1973).

Another metaluminous quartz alkalic magmatic suite occurs at Sugarloaf Peak in the Dome Rock Mountains of La Paz County western Arizona. This gold prospect was formed about 160 Ma and is known for zunyite crystals at the Big Bertha mine and for alunite.

3.2 Cretaceous Sevier Orogeny (140-89 Ma)

The stable (non-migrating and non-flattening) magmatic arc of the Sevier orogeny was located in California, with back arc basins located in Arizona and similar regions east of the magmatic arc. The best documented basin in Arizona is represented by continental and shallow marine sediments of the Bisbee Group and its correlative sedimentary sequences. These sandstones, siltstones, and limestones were deposited in a basin and nearby seaway that transgressed from the southeast, depositing the Mural Limestone in the Bisbee area (Dickinson and others, 1989). In mountain ranges to the north, the Bisbee Group is represented by sandstone and siltstone clastic rocks from deltaic or floodplain environments.

The Bisbee Group is a series of mostly clastic rocks that include maroon mudstone and siltstone, brown to buff sandstone, and a few thin limestone beds containing marine and fresh-water fossils.

The Mural Limestone represents the maximum extent of the mid-Cretaceous seaway into Arizona in the Bisbee area. It is a source of limestone for cement at Paul Spur east of Bisbee.

3.3 Laramide Orogeny (85 – 43 Ma)

Because the subduction zone became flatter throughout the Laramide orogeny (89 – 43 Ma), the magmatic arc migrated eastward through geologic time. Thus, later magmatism and mineralization overprinted the earlier episodes. The Laramide orogeny has been subdivided into four phases: the earliest, early, middle, and late phases (Keith and Wilt, 1986).

3.3.1 Cretaceous, Earliest Laramide (Hillsboro) (85-80 Ma) – Cu-Au Mineralization

The earliest phase of the Laramide orogeny (called the Hillsboro Assemblage) in southern Arizona is represented by small stocks of quartz alkalic chemistry, generally latites and monzonites with small volcanic centers (Keith and Wilt, 1986).

Examples are the Copper Flat stock at Hillsboro in New Mexico. Examples in western Arizona include the Mudersbach pluton in the central Plomosa Mountains. Examples in southern Arizona include native copper in the high potassium andesitic volcanics at La Colorado south of Arivaca (Keith, personal communication, 2013).

3.3.2 Cretaceous, Early Laramide (Tombstone) (79-67 Ma) – Pb-Zn-Ag Mineralization

The early Laramide phase is represented by lead-zinc-silver mineralization associated with caldera development of alkali-calcic volcanism and plutonism in southern Arizona. This phase was called the Tombstone Assemblage by Keith and Wilt (1986).

Throughout southern Arizona, the Tombstone Assemblage is characterized by large volcanic centers (calderas) that experienced large volumes of explosive volcanism and ash deposits. The basal sedimentary rocks are continental fluvial sandstones and conglomerates containing large exotic blocks ranging in size from cobbles to house-sized boulders of pre-existing rocks and having a volcanic matrix. 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. These sedimentary rocks containing exotic blocks are generally interpreted as caldera infill or moat deposits from the collapse of the volcanic edifice. The basal exotic block member is typically an andesitic to dacitic breccia with a pyroclastic breccia texture. The unit containing exotic blocks conformably grades upward into dacitic to ignimbritic rhyolitic flows or ash flows. The predominant rock types of the Tombstone Assemblage are the pyroclastic volcanic rocks that are up to 5,000 ft thick.

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. Although some of these have been interpreted either as laccolithic sills emplaced into their volcanic cover or as ash flow sheets, they are clearly related to the caldera volcanism. These igneous rocks plot in the alkali-calcic field of a K_2O versus (vs) SiO_2 variation diagram and are associated with lead-zinc-silver vein and replacement mineralization (Wilt, 1993).

The igneous activity of the Tombstone Assemblage is younger in eastern Arizona than in western Arizona. This indicates the alkali-calcic portion of arc magmatism moved eastward through time, as the subducting Farallon plate became shallower. Tombstone Assemblage magmatism in the vicinity of Tucson is about 80 to 70 Ma, whereas similar magmatism in New Mexico is 70 to 64 Ma. In the Tombstone Hills, the Tombstone Assemblage magmatism is 76 to 72 Ma.

Examples of the metaluminous alkali-calcic districts with lead-zinc-silver mineralization include the Tombstone, Tyndall (Glove mine), Washington Camp, and Salero mining districts. Mines in the Tombstone district had argentiferous lead sulfide ore in irregular replacement bodies along fissure zones and anticlinal rolls and contained zones that were deeply oxidized (Keith, 1973).

Mines in the Tyndall district in the western slope of the southern Santa Rita Mountains consisted of irregular lenses of quartz fissure veins containing argentiferous lead, zinc and copper with shallow oxidation and supergene enrichment (Keith, 1975). The Glove mine in Santa Cruz County is a small, oxide, lead-silver-zinc deposit that is located within an isolated block of Paleozoic and Cretaceous sediments intruded by Early Laramide latite porphyry sills. The mineralization and metamorphosed limestone beds (marble) are cut by a series of tight faults (Olson, 1966). The butterscotch yellow wulfenite specimens from the Glove mine are well known (Rasmussen, 2010).

The Duquesne – Washington group in the Patagonia district also are probable metaluminous alkali-calcic deposits. They consist of tabular to lensing, skarn and replacement deposits of sphalerite galena, chalcopyrite, and pyrite in Permian limestones adjacent to Laramide granodiorite (about 72 Ma old) and they are generally strongly oxidized (Keith, 1975).

3.3.3 Tertiary, Middle Laramide (Morenci) (66-55 Ma) - Porphyry Cu Mineralization

The middle Laramide phase is represented by porphyry copper deposits associated with porphyritic stocks of quartz diorite to granodiorite composition of metaluminous calc-alkalic magma chemistry in southern Arizona. This phase was called the Morenci Assemblage by Keith and Wilt (1986).

Numerous age dates on these porphyry copper deposits show that the deposits are also younger in the east than in the west. This indicates the calc-alkalic portion of arc magmatism moved eastward through time, as the subducting Farallon plate became shallower. Morenci Assemblage magmatism in northwestern Arizona is 75 to 70 Ma, in the Morenci area is 62 to 51 Ma, in eastern Arizona and New Mexico is 60 to 52 Ma, and in the Tombstone Hills is 66 to 62 Ma.

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.

These porphyry copper deposits are large, disseminated, mesothermal, annular zones of copper-molybdenum mineralization in or adjacent to porphyritic, epizonal, calc-alkalic stocks. The systems are extremely large and commonly exhibit zoning outward from the copper-rich core in this sequence: Cu-Zn; Zn-Pb-Ag-Au; Pb-Ag; and Ag-Mn. These disseminated systems locally contain skarn and vein deposits. Copper-zinc skarns occur adjacent to the plutons and copper-zinc-silver veins, skarns or replacements are more marginal to the plutons, and manganese occurrences are more distal.

3.4 Tertiary, Late Laramide (Wilderness) (54-43 Ma) – Tungsten (W) Mineralization

The latest Laramide phase in southern Arizona is represented by tungsten or gold-quartz vein deposits associated with garnet-muscovite granitoid stocks and pegmatite dikes of peraluminous, magma chemistry. This phase was called the Wilderness Assemblage by Keith and Wilt (1985, 1986). There are no sedimentary or volcanic rocks in the Wilderness Assemblage. Instead there are large volumes of peraluminous, muscovite- and garnet-bearing granitoids that commonly contain late alaskitic pegmatite sills and later cross-cutting dikes.

Many Wilderness Assemblage plutons are associated with well-developed mylonitic fabrics in or adjacent to the plutons and appear to be synkinematically intruded into southwest-directed mylonitic shear zones. This may represent a widespread southwest-directed thrust system caused by underthrusting the Farallon plate toward the northeast under the Colorado Plateau. This underthrusting raised the area to be eroded into the Eocene erosion surface. This thrust faulting episode may be represented in the Little Dragoon Mountains by the Lime Peak thrust fault.

The Wilderness Assemblage plutons and pegmatitic dikes and quartz veins intrude the earlier porphyry copper-related plutons and are generally younger to the east. This indicates the peraluminous portion of arc magmatism also moved eastward through time, as the subducting Farallon plate became so shallow that it was nearly flat. In the Little Dragoon Mountains, the main phase of the Texas Canyon pluton was intruded by the peraluminous calc-alkalic Adams Peak leucogranite. The age dates on the peraluminous plutons in the Coyote Mountains in southwestern Arizona is 58 Ma, and age dates on the Wilderness Granite in the Santa Catalina Mountains are 44-50 Ma.

In the Huachuca Mountains, tungsten mineralization is probably related to the muscovite-bearing peraluminous alaskites that locally occur in southwest-directed thrust faults. Hydrothermal sericite related to the tungsten mineralization there is dated at 48 Ma. An example of the Wilderness Assemblage mineralization is probably the Bluebird leucogranite in the Texas Canyon area.

The two types of peraluminous granites 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 (Keith and others, 1983).

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.

3.5 Galiuro Orogeny (43-13 Ma)

The Galiuro (mid-Tertiary) orogeny was subdivided into three phases as the subducting slab became steeper and the central axis of the magmatic arc moved from the east to the west, in the reverse pattern from the Laramide (Keith and Wilt, 1985). The Galiuro orogeny is subdivided into early (Mineta), middle (South Mountain – calc-alkalic and later Datil – alkali-calcic), and late (Whipple) phases.

3.5.1 Early Galiuro (Mineta phase) – 38-28 Ma

Sediments and volcanics of the early phase (Mineta) of the Galiuro orogeny were deposited in local basins. Rocks deposited during this time consisted of minor volcanics, local conglomerates and lacustrine deposits of carbonates and gypsum and clay. Minor mineral deposits consisted of minor uranium in sedimentary and volcanic rocks (Scarborough and Wilt, 1980), secondary exotic copper deposits, and industrial mineral deposits.

Although it is not obvious when the Late Laramide porphyry copper deposits were uplifted and eroded so that the chalcopyrite ore bodies were weathered and redeposited as exotic copper deposits, it is likely that this would have happened during the early Galiuro Orogeny. 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.

3.5.2 Middle Galiuro (South Mountain [30-22 Ma] and Datil [28-18 Ma] phases) -

The middle phase of the Galiuro orogeny consists of widespread volcanism and stocks of calc-alkalic and later alkali-calcic chemistry. The earlier calc-alkalic phase (called the South Mountain phase) contains epithermal gold-copper veins associated with microdiorite dike swarms. 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 calc-alkalic phase include the deposits in the Little Harquahala district and the mines in the Kofa district. Examples of the alkali-calcic phase include deposits of the Silver (Red Cloud mine), Castle Dome, Stanley, and Aravaipa mining districts.

3.5.3 Late Galiuro (Whipple phase) – 189-13 Ma

The latest (Whipple) phase of the Galiuro orogeny 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.

3.5.4 San Andreas Orogeny (Basin and Range Disturbance) - 13-0 Ma

The present physiography of the Basin and Range Province was produced by the tectonics associated with the movement of the San Andreas transform fault and concurrent compression creating the transverse ranges (Harcuvar and Harquahala Mountains and others in California). This orogenic phase was named the San Andreas orogeny by Keith and Wilt (1985, 1986).

The San Andreas Orogeny (Basin and Range Disturbance) is 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
	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 m.), 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

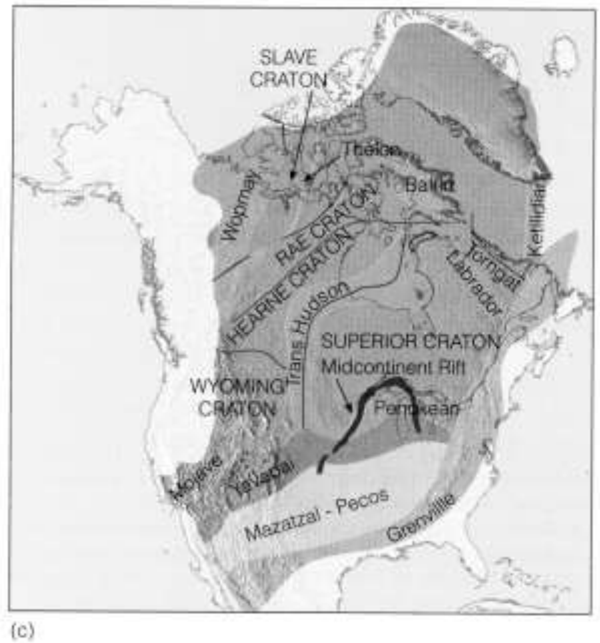

FIGURE 9.2 Proterozoic evolution of the Laurentian craton. (a) During the Early Proterozoic, Archean cratons were sutured along deformation belts called *orogens*. (b) Laurentia grew along its southern margin by accretion of the Central Plains, Yavapai, and Mazatzal orogens. (c) A final episode of Protoerozoic accretion occurred during the Grenville orogeny.

Source: Wicander and Monroe, 2000

Figure 1. Proterozoic mountain belts added to the North American craton

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