Geology of the Northern Santa Rita Mountains, Arizona

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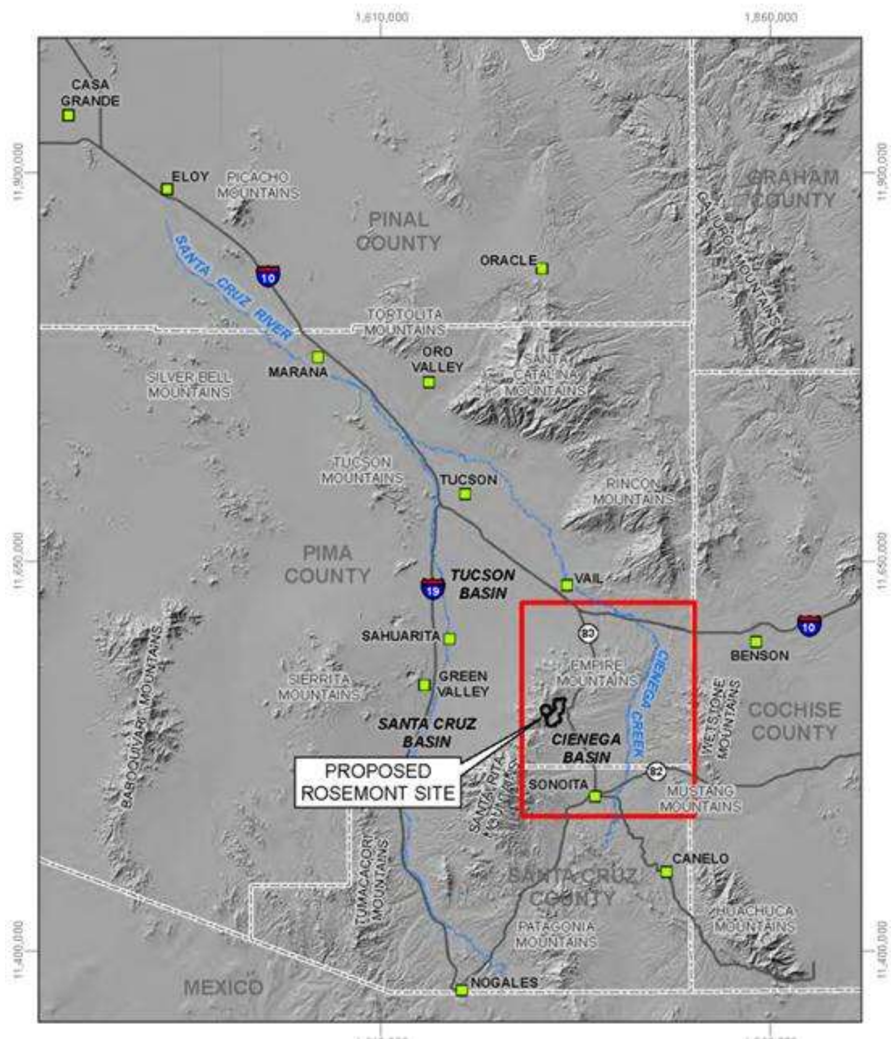
1 Introduction

The Arizona Geological Society Fall Field Trip will visit a number of outcrops in the northern Santa Rita Mountains, in the area of the proposed Rosemont Copper project. This article will provide a brief summary of the geology of this part of the range.

1.1 Location

The Rosemont copper-molybdenum-silver deposit is located in Pima County, Arizona, USA on the northeastern flank of the Santa Rita Mountains approximately 30 miles southeast of the city of Tucson (Figure 1). The Rosemont property occupies flat to mountainous topography at a surface elevation ranging from 4,000 feet to 6,290 feet and at geographical coordinates of approximately 31° 50' N and 110° 45' W (M3, 2012).



Source: Montgomery & Associates (2009)

Figure 1 Location of northern Santa Rita Mountains and the Rosemont project area

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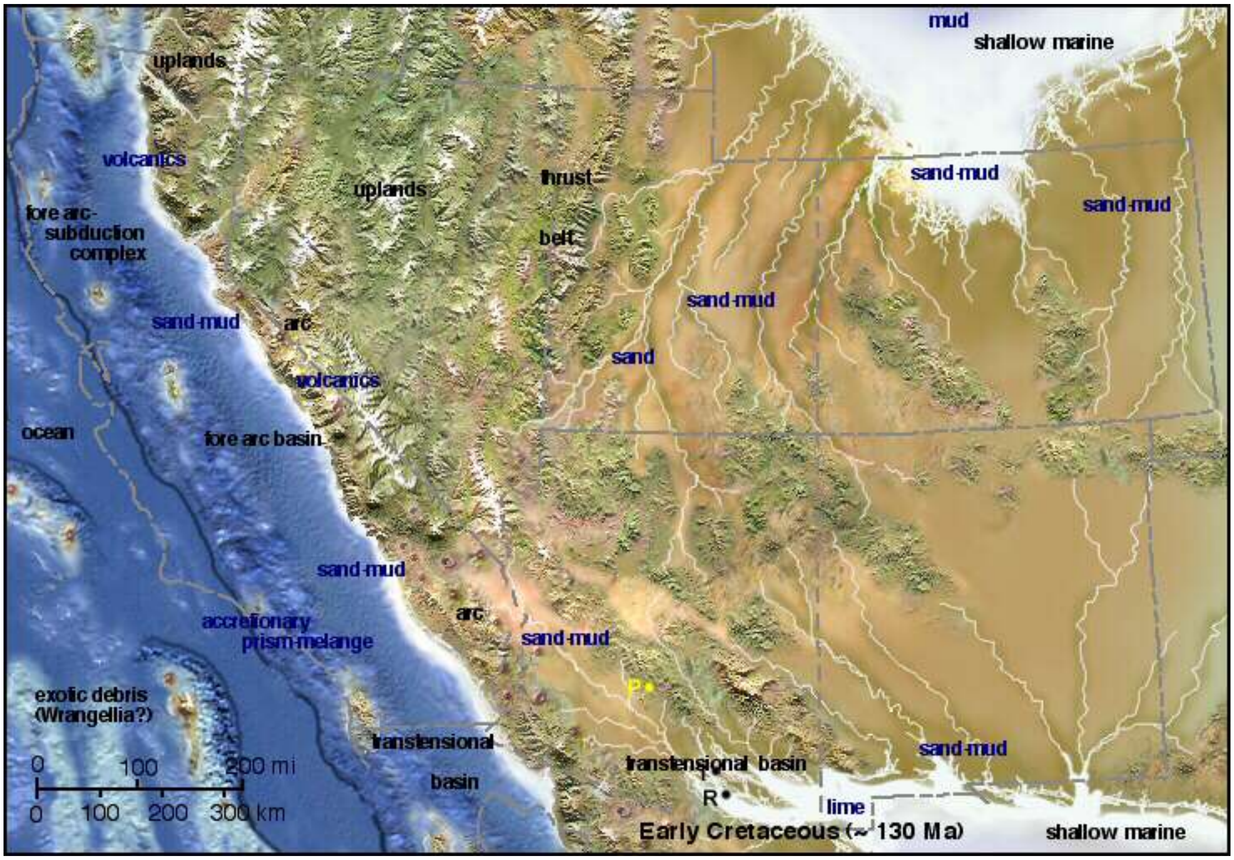
The best documented basins in Arizona are represented by continental and shallow marine sediments of the Bisbee Group and its correlative sedimentary sequences. These sandstone, siltstone, and limestone formations were deposited in a seaway that transgressed from the southeast, depositing the Mural Limestone in the Bisbee area (Dickinson et al., 1989), which transitioned to nearshore deltaic and alluvial basins just north of Bisbee (Figure 2 from Blakey, 2012). The Bisbee Group in most of southern Arizona is a series of clastic rocks that include maroon mudstone and siltstone, brown to buff sandstone, and a few thin limestone beds containing marine and fresh-water fossils.



Source: Modified from Ron Blakey, NAU; Accessed July 7, 2012 from http://jan.ucc.nau.edu/rcb7/crepaleo.html
Notes: Dots show the location of Phoenix (P, yellow), Tucson (T, black), and Rosemont (R, black) . The "shallow marine" area shown in north-central Colorado and much of Wyoming is the epicontinental Western Interior Seaway. The "shallow marine" area shown in southeastern Arizona, southwestern New Mexico and Chihuahua, Mexico is an embayment of the Western Interior Seaway called the Chihuahua trough. The Bisbee basin is the northernmost portion of the Chihuahua trough as it is documented in southeastern Arizona.

Figure 2 Paleogeographic reconstruction of North America in Early Cretaceous (130 Ma)

2.4 Laramide Orogeny (Late Cretaceous and Early Tertiary)

The Laramide orogeny can be divided into several episodes that sequentially affected southern Arizona at intervals of about 10 million years. These four parts of the Laramide orogeny are characterized by different structures, magmatic chemistry, types of ore deposits, and types of volcanism and plutonism.

In earliest part of the Laramide orogeny in the Late Cretaceous (approximately 80 Ma), the north-south compression of Gilluly (1956) also called the early Late Cretaceous disturbance by Hayes (1970) created west- or west-northwest-striking block uplifts along high-angle reverse faults. The isoclinal folding in the Bisbee Group sedimentary rocks was probably also created during this time (Keith and Wilt, 1986).

In the Late Cretaceous (early part of the Laramide orogeny), another major volcanic mountain building episode created numerous separate volcanic centers and calderas, such as the Salero volcanics in the southern Santa Rita Mountains (Keith and Wilt, 1986). These rocks are associated with the early Laramide (approximately 75 Ma) lead-zinc-silver mineralization of the Empire, Tyndall, Old Baldy, and Salero mining districts in the Empire and Santa Rita Mountains.

In the early Tertiary (middle part of the Laramide orogeny at approximately 65 Ma), slight changes in the direction of subduction allowed earlier formed fractures and faults (the Texas Zone) to open and be intruded by dikes and stocks of quartz monzonite. These intrusions were accompanied by porphyry copper-molybdenum mineralization in the northern Santa Rita Mountains in the Helvetia-Rosemont mining districts.

Later in the early Tertiary (latest part of the Laramide orogeny at approximately 45 Ma), large volumes of peraluminous, muscovite- and garnet-bearing granitoids occur in the deepest parts of some mountain ranges. An example is the Wilderness granite in the Santa Catalina and Rincon Mountains (Keith et al., 1980). These batholithic plutons also contain late alaskitic pegmatite sills and later dikes, all of which cross cut the earlier Laramide porphyry copper-related intrusions. Many Wilderness Assemblage plutons are associated with well-developed mylonitic fabrics in or adjacent to the plutons and these dikes and plutons 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, thus raising the area to be eroded into the Eocene erosion surface. Some of these Wilderness suites are associated with tungsten deposits (Keith and Wilt, 1985).

2.5 Mid-Tertiary Orogeny

In the mid-Tertiary, another volcanic mountain building episode created volcanic centers and calderas throughout southern Arizona, such as near Nogales and the northern Tucson and Galiuro Mountains (Keith and Wilt, 1985). The mid-Tertiary (also known as Galiuro) orogeny is subdivided into early, middle, and late phases.

The early phase of the Galiuro orogeny consisted of sediments deposited in local basins containing minor volcanics, local conglomerates and lacustrine deposits of carbonates. Gypsum and clay deposits occur in these lake beds and minor uranium, secondary copper, and other industrial mineral deposits are also present.

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 contains epithermal Au-Cu veins associated with microdiorite dike swarms. The later alkali-calcic phase contains Pb-Zn-Ag skarns and replacements in contact zones of stocks and small batholiths, associated with large caldera systems. Possible Galiuro orogeny dikes cross cut earlier rocks in the northern Santa Rita Mountains.

The late phase of the Galiuro orogeny consists of coarse clastics and local volcanics and stocks of quartz-alkalic magma chemistry, associated with large, low-angle, normal detachment faults. Mineral resources consist of Cu-Au-Ag specularite replacement lenses, veins and disseminations in low-angle faults, and syngenetic stratabound uranium in lake beds and tuffs.

2.6 Basin and Range Disturbance

Finally, in the Late Tertiary, the Basin and Range Disturbance dropped the basins to their present position and created the current mountain ranges (Keith and Wilt, 1985). The 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.

3 Stratigraphy

The geology of the Santa Rita Mountains is among the most well-known in the Coronado National Forest (CNF) management units according to observations by geologists with the U.S. Geological Survey (DuBray, 1996; Drewes, 1996). This section is primarily extracted from the Draft Environmental Impact Statement (Draft EIS) published on the internet for public comment (CNF, 2011). Some additional information is quoted from geologic mapping by the U. S. Geological Survey (USGS) (Drewes, 1971) and the Arizona Geological Survey (Ferguson et al., 2001; Johnson and Ferguson, 2007; Ferguson et al., 2009). A generalized geologic map of the Santa Rita Mountains is shown in Figure 3 (Drewes et al., 2002).

The general geology of the northern Santa Rita Mountains differs from that in the southern Santa Rita Mountains (see Figure 3 map). The northern block (north of the Sawmill Canyon fault zone) is primarily Precambrian granite (brown on the map), with some slices of Paleozoic and Mesozoic sediments on the eastern and northern sides (blue and green on the map). This block includes some early Tertiary (middle Laramide) small stocks and dikes of quartz monzonite or quartz latite porphyry that are related to porphyry copper mineralization. These include historic mines in the Cuprite, Helvetia, Rosemont, Box Canyon, Greaterville, and Jackson mining districts (Keith et al., 1983).

The southern block consists primarily of Triassic-Jurassic volcanic and sedimentary rocks (pale blue on the map), Jurassic granite (dark green), Early Cretaceous volcanic and sedimentary rocks (green), and Late Cretaceous dacite and rhyolite (pale green), and quartz monzonite and granite (tan on the map). The mining districts in the southern block include the Old Baldy, Cave Creek, Wrightson, Tyndall, Mansfield, and Salero districts that historically primarily produced lead-zinc-silver (Keith et al., 1983).

A geological map showing the rock formations of the project area is shown in Figure 4. Figure 5 shows an east-west geological cross section showing the surface and subsurface rock formations in the area of the proposed open pit and dry-stack tailings. The geology of the Rosemont area is described at regional and local scales by Schrader (1915), Drewes (1971; 1972a; 1972b), duBray (1996), Hardy (1997), Ferguson et al. (2001), Johnson and Ferguson (2007), Ferguson (2009), and Ferguson et al. (2009).

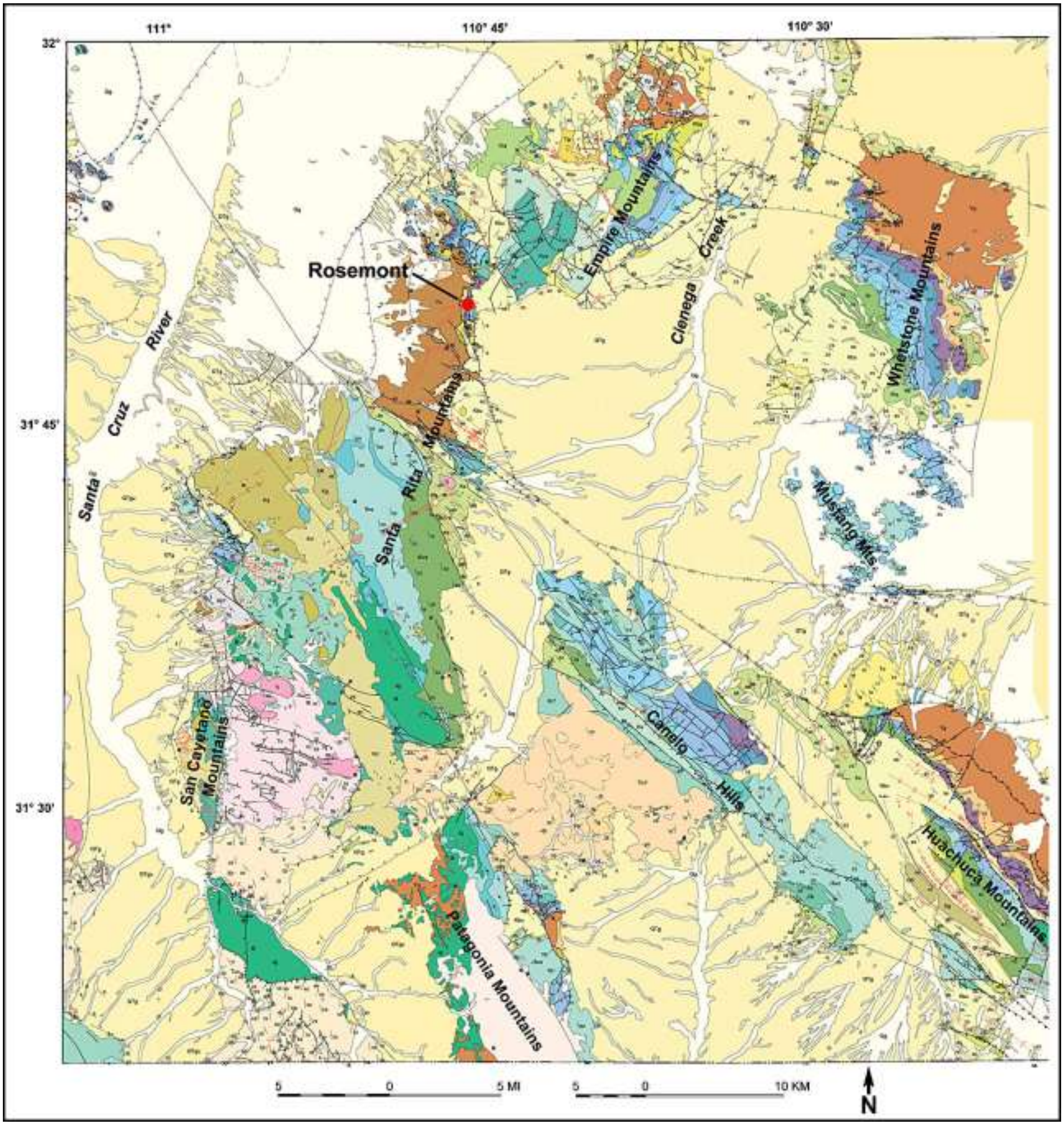
Igneous rocks in the Santa Rita Mountains are of Proterozoic, Triassic-Jurassic, Late Cretaceous, early Tertiary (Laramide), and mid-Tertiary age. Proterozoic granitic rocks crop out on the crest of the Santa Rita Mountains and down the western slope in the Rosemont-Helvetia area. Mapped rock types include granite, quartz diorite, quartz monzonite, and associated aplite. Small, Laramide intrusions (stocks) of quartz monzonite and quartz latite occur in the Rosemont project area, and larger stocks of similar composition occur to the north at Broadtop Butte and west in the Helvetia area.

A general stratigraphic section of the major rock units in the district is provided in Figure 6. Descriptions of the principal units found in the Rosemont deposit area and the approximate thicknesses of the units are presented below. The summaries are based on information compiled by Johnson and Ferguson (2007), on descriptions of Rosemont drill core (Augusta Resource Corporation, 2007; Daffron et al., 2007), and from the Draft EIS (CNF, 2011). Descriptions of the stratigraphic units are summarized in the following section, from oldest to youngest.

Table 1 Mesozoic-Cenozoic orogenic episodes in southern Arizona

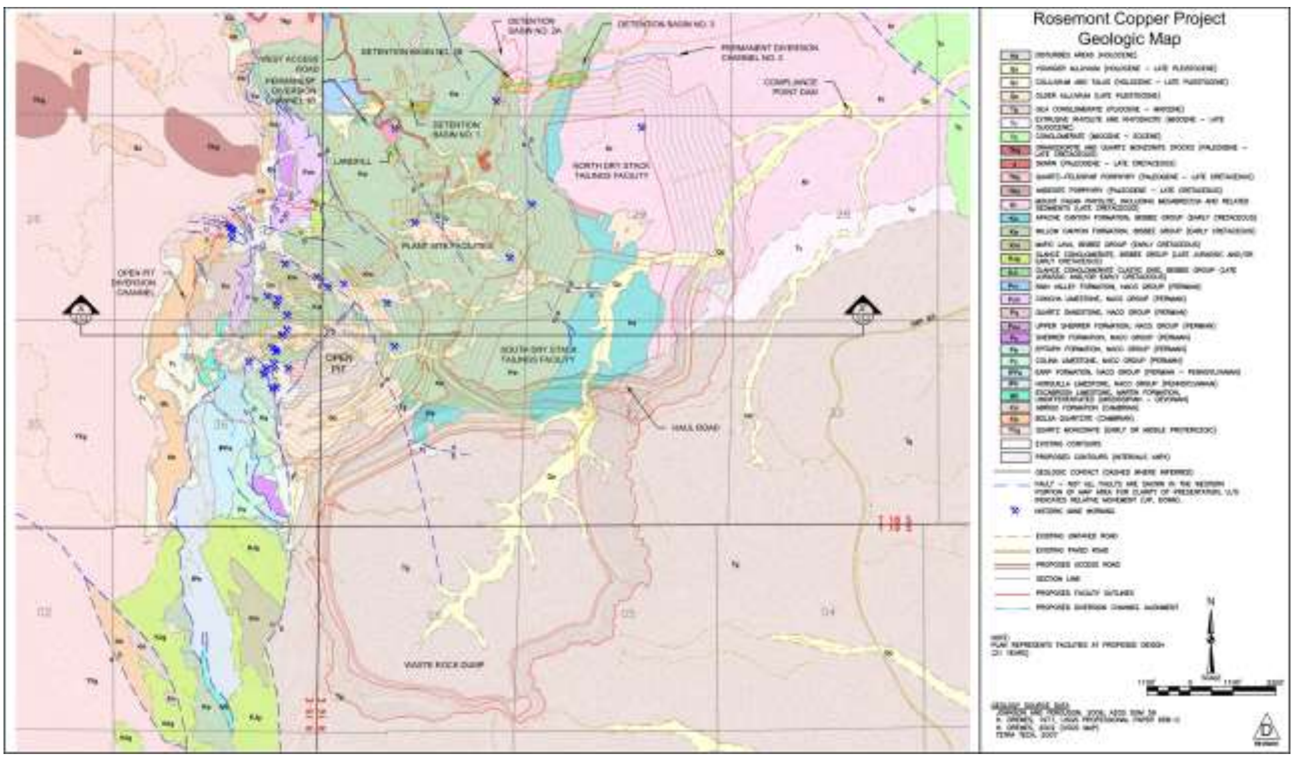
Orogeny	Phase	Age Ma	Sediments	Magmatism	Structures	Resources
Basin & Range		13-0	clastics & evaporites in grabens, alluvium	alkaline anhydrous basaltic volcanism	N-S trending horsts & grabens, bounded by steep normal faults	sand & gravel, salt, zeolites, cinders, gypsum
mid-Tertiary	Late	18-13	coarse to fine clastics, megabreccia blocks; Gila Conglomerate	alkalic hydrous volcanics & local epizonal stocks	low-angle normal detachment faults, SSE-trending folds, NW striking thrusts & reverse faults	Cu-Au-Ag in veins, replacement lenses & in detachment faults, epithermal Au-Ag veins, hotspring Mn & U
	Middle	28-18	local clastics interfinger with volcanics	alkali-calcic hydrous ignimbritic volcanics & epizonal plutons & dikes	broad NW-trending folds; NW- and NE-trending dikes	Pb-Zn-Ag +/- F in veins, replacements, epithermal Ag, hotspring Mn
	Middle	30-22	local clastics interfinger with volcanics	calc-alkalic hydrous volcanics & epizonal plutons	broad NW-trending folds, NW-trending dikes, minor NE-trending dikes	Au +/- Cu-W veins & disseminated deposits
	Early	38-28	coarse & fine clastics, evaporites, lake beds - Pantano Fm.	rare volcanics, mostly within 'volcanic gap"	local broad basins; possibly with WNW trend; reverse faults	U, clay, exotic Cu
Laramide	Late	55-43	none	widespread, 2-mica, garnet-muscovite granitic stocks, sills, aplo-pegmatite dikes, peraluminous	SW-directed, low-angle thrusts widespread, shallowly dipping mylonitic zones, general SW shear	mesothermal, Pb-Zn-Ag veins, minor Cu-Au veins, Au in quartz veins, kyanite, tungsten
	Middle	65-55	none	calc-alkalic stocks (andesite porphyry, quartz feldspar porphyry) & NE to ENE-striking dikes	widespread NE- to ENE-striking regional dike swarms between E-W to ENE striking structural elements of the Texas Zone that moved in left-slip	large disseminated porphyry Cu systems, locally containing skarns & veins; Cu-Zn-Ag veins;
	Early	85-65	continental; large exotic blocks interbedded volcani-clastics: Salero Fm., Ft. Crittenden Fm.	alkali-calcic, volcanics (Mt. Fagan Rhyolite; Mount Wrightson Fm.) & quartz monzonite porphyritic stocks (Madera Canyon, Elephant Head; Corona de Tucson)	NW-striking, NE-directed folds & thrusts with 1-10 km shortening	mesothermal, Pb-Zn-Ag veins & replacement deposits
	Earliest	89-85	coarse continental clastics; lack of volcanics except in upper parts; angular unconformity over mid-Cretaceous	quartz alkalic hydrous, volcanics 7 small stocks, small volcanic centers, small epizonal porphyritic stocks; volcanics highly brecciated; latite & monzonite	E-W block uplifts; E-W to WNW-ESE striking high-angle reverse faults with shortening 5-7 km vertical throw, 1-3 km horizontal throw; bidirectional transport N- or S-directed or NNE= or SSW-directed either side of block uplifts	epigenetic Cu-Au hydrothermal
Sevier	Late	105-89	Bisbee Group; Shellenberger Canyon, Turney Ranch Fm.	none		
	Middle	120-105	Bisbee Group clastics: Willow Canyon, Apache Canyon Fm.	none	gentle NE-striking basin for transgressive seaway	limestone
	Early	145-120	Glance Conglomerate	volcanic pause		
Nevadan	Late	160-145	Lower Glance Conglomerate	Mt. Wrightson Volcanics	WNW Texas zones as shear zones	
	Middle	205-160	Eolian ss intercalated with volcanics	Canelo Hills volcanics; plutonic rocks	WNW-striking Texas zones as grabens	porphyry Cu-Au at Bisbee, Gleeson
	Early	230-205	continental red beds (ss, sh)	Gardner Canyon Formation		

Source: Keith and Wilt (1985, 1986)



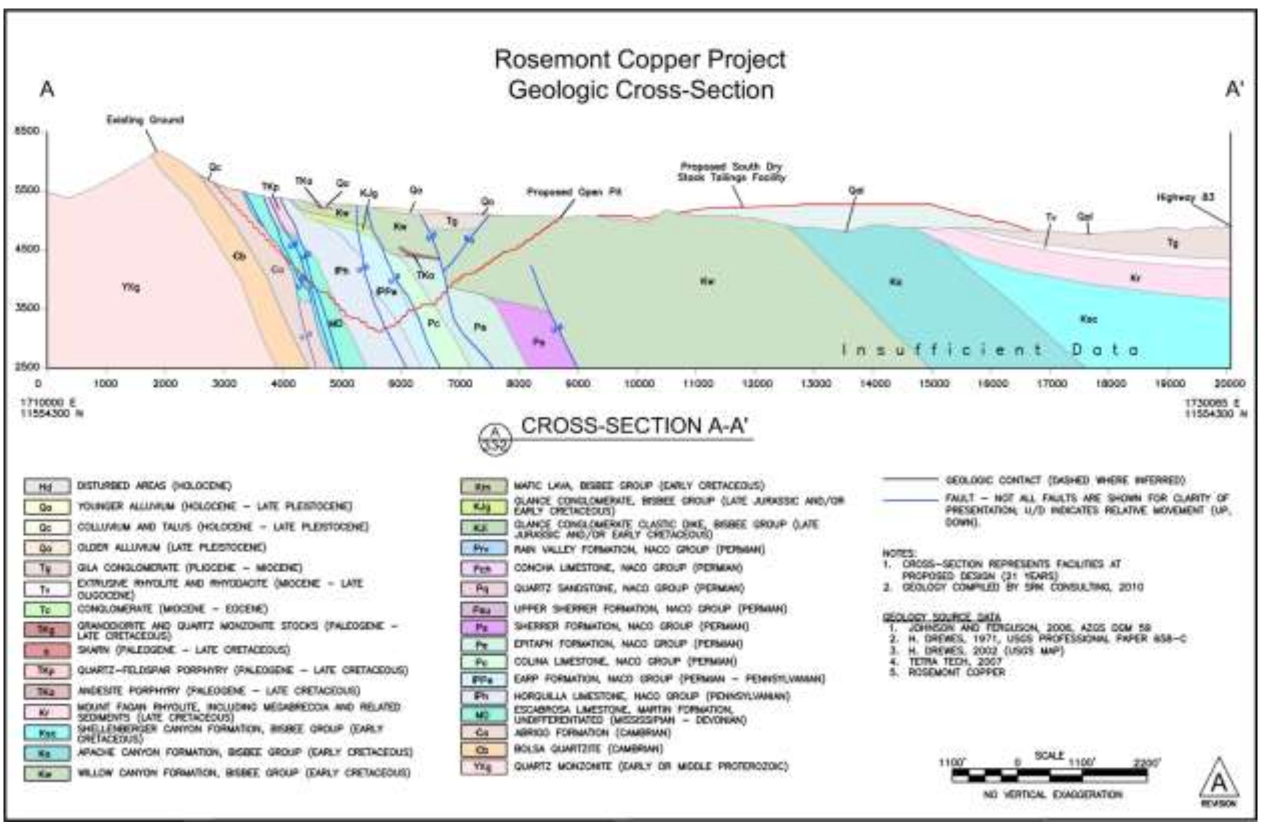
Source: Drewes (1971); Drewes et al. (2002)

Figure 3 Geologic map of the Santa Rita Mountains and nearby areas



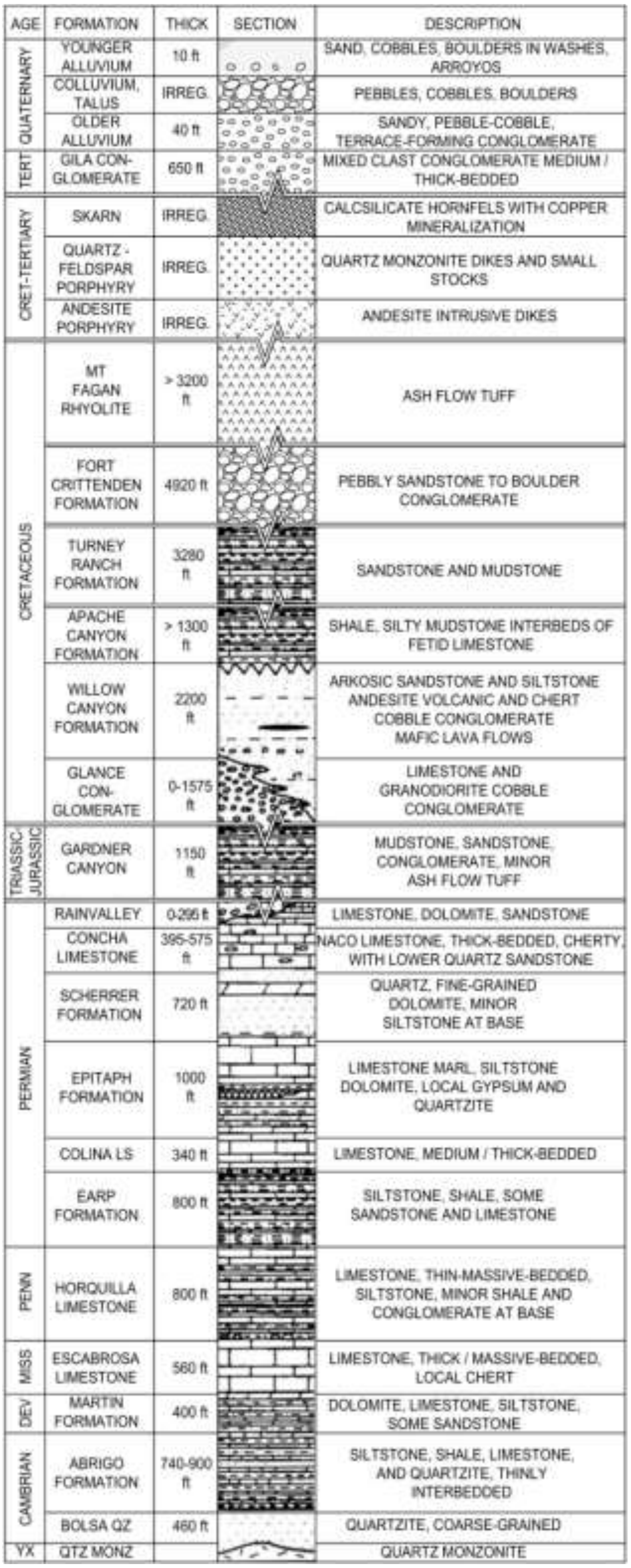
Source: Adapted from Johnson and Ferguson (2007) and Drewes (1971)

Figure 4 Geologic map of the Rosemont project area



Source: Adapted from Johnson and Ferguson (2007); Drewes (1971).

Figure 5 Cross section of Rosemont Copper project



Source: Draft EIS (CNF, 2011, Figure 3.3). Adapted from Anzalone (1995), after McNew (1981) and Johnson and Ferguson (2007). Illustration is not to scale. Unit thicknesses vary, and not all units are present throughout the area. Broken lines indicate unconformable contacts. Intrusive rocks crosscut various units. Tertiary conglomerate and Quaternary alluvium overlie all older units.

Figure 6 General stratigraphic section of major rock units in the district

3.1 Proterozoic Era

The northern Santa Rita Mountains and Rosemont area contain a sequence of Proterozoic intrusive rocks overlain by carbonate rocks, quartz sandstone, siltstone, and basin-fill formations. The bedrock units are crosscut by andesite dikes and quartz monzonite dikes and stocks; mafic lava flows are found in selected basin-fill units.

The Pinal Schist occurs in the northeastern part of the Mount Fagan quadrangle and in the Helvetia quadrangle, but does not crop out in the Rosemont project. It is a silvery gray, fine-grained, crenulated, quartz-biotite schist Ferguson et al., 2001; 2009).

The Continental Granodiorite of Early or Middle Proterozoic age ranges in composition from granodiorite to quartz monzonite, unmeasured thickness). In the Helvetia quadrangle, it is medium grained and contains 5-35% distinctive pink potassium feldspar megacrysts up to 5 cm long (Ferguson, et al., 2009). In the Rosemont area, it is a medium-grained, quartz monzonite with 15% to 20% altered dark minerals (Johnson and Ferguson 2007).

3.2 Paleozoic Era

The stratigraphic sequence in the northern Santa Rita Mountains includes, from oldest to youngest, the Bolsa Quartzite and Abrigo Limestone (both of Cambrian age); Devonian Martin Formation; Mississippian Escabrosa Limestone; Pennsylvanian Horquilla Limestone; Earp Formation (Pennsylvanian to Permian age); and Colina Limestone, Epitaph Formation, Scherrer Formation, Concha Limestone, and Rainvalley Formation (all of Permian age).

Cambrian Period

Bolsa Quartzite. The Bolsa Quartzite in southern Arizona is of probable Middle Cambrian age (~521-499 Ma) and represents the beach sand deposits of a transgressing seaway. In the Mount Fagan quadrangle it is light pinkish gray to purplish red, medium- to coarse-grained quartz sandstone (Ferguson et al., 2001). In the Helvetia quadrangle it is also light to medium gray, medium- to fine-grained, thick- to medium-bedded quartzose sandstone forming cliffs and ledges (Ferguson et al., 2009).

The Bolsa Quartzite is 260–570 feet thick in the Rosemont area, where it consists of light gray, medium- to fine-grained, thick- to medium-bedded, quartzose sandstone that forms cliffs and ledges. The lower part is cross stratified, commonly coarse grained, and locally feldspathic, with composition apparently ranging from quartz arenite to subarkosic arenite. Pebbly to granular beds occur near the base of the unit, which unconformably overlies quartz monzonite. The upper part of the Bolsa Quartzite is medium gray, fine-grained, and commonly bioturbated with *Planolites* ichnofossils (traces of ocean-bottom burrows) and includes as much as 30% silty mudstone or shale near the gradational contact with the overlying Abrigo Formation (CNF, 2011).

Abrigo Formation. The Abrigo Formation in southern Arizona is of probable Middle to Late Cambrian age (~515-488 Ma) and represents the nearshore deltaic and deeper marine carbonate facies of a transgressing seaway. In the Mount Fagan quadrangle, it consists of interbedded, thin-to medium-bedded greenish-gray calcareous siltstone, silty shale, shale, and variable sandy limestone and dolostone that becomes more carbonate rich higher in the section (Ferguson et al., 2001). In the Helvetia quadrangle, it contains fine-grained sandstone interbedded with siltstone, silty mudstone, and shale in the lower part. In much of the area it has been metamorphosed to fine-grained marble and light pinkish-gray to greenish-yellow calc-silicate hornfels that form resistant outcrops (Ferguson et al., 2009).

The Abrigo Formation is 330–660 feet thick in the Rosemont area, where it consists of a sequence of thin- to medium-bedded limestone with siliceous lamination. The lower part contains intercalated fine-grained, parallel-laminated to ripple-laminated, fine-grained sandstone, siltstone, silty mudstone, and shale. Locally, the unit has partly been metamorphosed to light pinkish gray to greenish yellow, calc-silicate hornfels that form resistant outcrops with recessive, thin beds, lenses, and laminations (CNF, 2011).

Devonian Period

Martin Formation. The Martin Formation in southern Arizona is of probable Late Devonian age (~386-375 Ma) and consists of 350 to 500 feet of dark-gray, medium-bedded, ledge-forming, yellowish brown weathering limestone with some pinkish shale and olive-gray dolomite. In the Mount Fagan quadrangle, the Martin Formation is a massive to very thick-bedded, light gray to white, sugary, micritic dolostone (Ferguson et al., 2001). In the Helvetia quadrangle, the Martin Formation consists of medium-bedded, gray to brown to tan limestone and dolostone (Ferguson et al., 2009).

In the Rosemont area, the Devonian Martin Formation and Mississippian Escabrosa Limestone are described as an undifferentiated unit. The Escabrosa Limestone – Martin Formation undifferentiated is 230–560 feet thick and consists of light gray, medium- to thick-bedded, amalgamated, massive, locally cherty, recrystallized limestone. Massive dolostone or dolomitic limestone locally is present in the lower section. Although an unconformity is present between the Martin Formation and the Escabrosa Limestone, these units are not preserved well enough in this area to distinguish between them (CNF, 2011).

Mississippian Period

Escabrosa Limestone. The Escabrosa Limestone in southern Arizona is of probable Early Mississippian age (~353-340 Ma) and consists of thick bedded limestone that forms very steep cliffs. It is typically a thick-bedded, coarse-grained, light-gray limestone with a large amount of crinoid fragments. In the Mount Fagan quadrangle, it is a massive to thick-bedded and very thick-bedded, cherty, recrystallized limestone or coarsely crystal marble (Ferguson et al., 2001). In the Helvetia quadrangle, it is also a light gray to white, thick-bedded, massive limestone that is typically metamorphosed to medium- to coarse-grained marble (Ferguson et al., 2009).

Pennsylvanian Period

Horquilla Limestone. The Horquilla Limestone in southern Arizona is of probable Middle to Late Pennsylvanian age (318-299 Ma) and consists of thin-bedded, blue-gray limestones alternating with thin beds of red shale and shaly limestone. Its weathered appearance from a distance looks like steps. In the Mount Fagan quadrangle, the Horquilla Limestone is medium- to thick-bedded, gray, cherty limestone with interbeds of thin- to medium-bedded, silty, greenish-gray shale and micritic limestone, with abundant recrystallization (Ferguson et al., 2001). In the Helvetia quadrangle, the Horquilla Limestone is a thick- to thin-bedded, light gray to white, fine-grained, cherty, recrystallized limestone. It contains interbedded shale, silty mudstone, and fine- to very fine-grained quartzose sandstone that are metamorphosed to hornfels that form resistant ribs (Ferguson et al., 2009).

In the Rosemont area, the Horquilla Limestone is 660–980 feet thick and is the major host for mineralization. It consists of light gray, thin- to thick-bedded, cherty limestone with interbeds of dark gray to green silty mudstone and shale that become more abundant higher in the section. The limestone composition and texture have been overprinted by skarn associated with the mineralizing event (CNF, 2011).

Permian Period

Earp Formation. The Earp Formation in southern Arizona is of Late Pennsylvanian age (~302-283 Ma) and consists of thin shaly limestones, reddish shale, thick limestone, and dolomite beds that weather orange or reddish. In the Mount Fagan quadrangle, the Earp Formation is a greenish-gray, light brown, and pale red, thin- to medium-bedded, quartz sandstone and quartz sandstone with sparse, thin-bedded limestone. A thin lenticular bed of chert pebble conglomerate occurs about 100 meters above the base (Ferguson et al., 2001). In the Helvetia area, the Earp formation is a mixed siliciclastic-carbonate unit consisting of light reddish brown to light green, thin- to medium bedded mudstone, siltstone, and very fine-grained sandstone. It is interbedded with light gray to pinkish gray micritic limestone and skeletal wackestone. These units are commonly metamorphosed to light green or orange- pink hornfels and fine-grained marble (Ferguson et al., 2009).

In the Rosemont area, the Earp Formation is 490–660 feet thick. It is a mixed siliciclastic-carbonate unit consisting of light, reddish brown to light green, thin- to medium-bedded, planar-laminated siltstone, silty mudstone, and very fine-grained sandstone that is intercalated with light gray to pinkish gray, thick-bedded, micritic limestone and skeletal wackestone. The siliciclastic components commonly are metamorphosed to light green or orange-pink hornfels (CNF, 2011).

Colina Limestone. The Colina Limestone is of probable late Early Permian age (Wolfcampian or ~283-277 Ma) and consists of dense, black limestone with some major beds of shale and sandstone. In the Mount Fagan quadrangle, the Colina Limestone consists of thick-bedded, medium to dark gray, micritic (fine-grained) limestone and commonly contains abundant millimeter-scale, white calcite veins (Ferguson et al., 2001). In the Helvetia quadrangle, the Colina Limestone is also medium- to thick-bedded, white to light gray, micritic limestone. In both areas, the unit has been metamorphosed to fine-grained marble (Ferguson et al., 2009).

In the Rosemont area, the Colina Limestone is 165–540 feet thick and consists of a light gray to white, medium- to thick-bedded, amalgamated, commonly dolomitic, micritic carbonate and skeletal wackestone. It is commonly metamorphosed to fine-grained marble (CNF, 2011).

Epitaph Formation. The Epitaph Formation is of late Early Permian age (Leonardian or ~279-275 Ma) and consists of dolomite with knots of silica, limestone, red shale, thin sandy layers. The maximum thickness of the Epitaph Dolomite is 785 ft in the type area, although the thickness varies as dolomitized Colina units are included in the Epitaph Formation. In the Mount Fagan quadrangle, the Epitaph Formation is a tripartite unit consisting of dolostone, limestone, siltstone, and gypsum, with the medial member containing the gypsum and siliciclastic rocks (Ferguson et al., 2001). In the Helvetia quadrangle, the Epitaph Formation also is a mixed unit consisting of white to medium gray, thin- to thick-bedded limestone and dolostone and a middle siliciclastic unit of thin- to medium-bedded siltstone, mudstone, and fine-grained sandstone. These units are commonly metamorphosed to fine-grained marble and light green hornfels (Ferguson et al., 2009).

In the Rosemont area, the Epitaph Formation is 820–1,280 feet thick. It is a mixed siliciclastic-carbonate unit. The siliciclastic units are purple to reddish, thin- to medium-bedded siltstone and silty mudstone, and a fine-grained, laminated sandstone. These units commonly are metamorphosed to light, orange-pink or greenish hornfels or are completely replaced with skarn mineralization, such as quartz, garnet, diopside, and sulfide minerals. The carbonate units are light gray to pink, micritic carbonates (CNF, 2011).

Scherrer Formation. The Scherrer Formation in southern Arizona is of late Early Permian age (Leonardian or ~275-272 Ma) and consists of three units from bottom to top: red siltstone, dolomitic limestone, and massive sandstone. In the Mount Fagan quadrangle, the Scherrer Formation is also a tripartite unit consisting of quartz sandstone with a medial carbonate unit. The lower unit is light yellowish-brown, fine- to medium-grained cross-stratified quartz sandstone. The middle unit is gray to pale orange, thin-to medium-bedded dolostone and dolomitic limestone. The upper unit is again a light-gray to pinkish-gray, fine- to medium-grained, calcareous, cross-stratified, quartz sandstone (Ferguson et al., 2001). In the Helvetia quadrangle, the Scherrer Formation is primarily a white to pin, fine-grained, planar-laminated quartz sandstone (Ferguson et al., 2009).

In the Rosemont area, the Scherrer Formation is 1,080–1,610 feet thick and generally consists of light gray to pink, fine-grained, massive, quartzose sandstone with rare laminations. The upper portion locally is differentiated as a transitional interval consisting of cream-colored, medium-bedded, dolomicrite with poorly preserved siltstone and argillaceous carbonate rocks (CNF, 2011).

Concha Limestone. The Concha Formation in southern Arizona is of late Early Permian age (Leonardian or ~272-270 Ma) and consists of light gray, cherty limestone with some sand layers at the base. In the Mount Fagan quadrangle, the Concha Limestone consists of thick-bedded limestone with abundant chert nodules, but contains sandy intervals and dolostone near the base. The limestone is typically recrystallized (Ferguson et al., 2001). In the Helvetia quadrangle, the Concha Limestone consists of dark to medium gray, thick- to medium-bedded, fossiliferous limestone that commonly contains large chert nodules (Ferguson et al., 2009).

In the Rosemont area, the Concha Limestone is 660–820 feet thick and consists of light to medium gray, medium- to thick-bedded, massive to planar-laminated, amalgamated, cherty limestone. Chert nodules characteristically are wispy and poorly formed. Locally dolomitic, the limestone is mostly micritic but includes skeletal wackestone and possible packstone, which locally contain spiculite beds and brachiopod fragments (CNF, 2011).

Rainvalley Formation. The Rainvalley Formation is of late Early Permian age (Leonardian or ~272-270 Ma) and consists of thin-bedded limestones. The Rainvalley differs from the underlying Concha in that its limestones are more varicolored, thinner bedded, more dolomitic, and more silty than those in the Concha. It contains less chert and includes some sandstone and siltstone beds, which produce a more subdued ledge and slope topography above the massive, generally cliff-forming Concha Limestone. The Rainvalley Formation gradationally overlies the Concha Limestone. Much or all of the Rainvalley has been removed by erosion in many places. In the Mount Fagan quadrangle, the Rainvalley Formation is thin- to medium-bedded, slightly cherty limestone with local thin beds of yellowish-gray to pinkish-gray, fine- to medium-grained quartz sandstone and sandy limestone (Ferguson et al., 2001). In the Helvetia quadrangle, the Rainvalley Formation is light to dark gray, thick-to medium-bedded dolostone and limestone, interbedded with minor fine- to medium-grained quartzose sandstone and siliceous shale (Ferguson et al., 2009).

In the Rosemont area, the Rainvalley Formation can be 330 feet thick. It consists of gray, medium- to thick-bedded limestone, intercalated with subordinate thin-bedded to laminated, locally ripple-laminated, fine-grained sandstone and siltstone. The unit is generally present in the Santa Rita Mountains, but is not found in certain areas as a result of erosion before the Mesozoic volcanic and sedimentary rocks were deposited (CNF, 2011).

3.3 Mesozoic Era

Mesozoic rocks in the northern Santa Rita Mountains consist (from older to younger) of the following:

- Triassic-Jurassic Gardner Canyon Formation,
- Jurassic-Cretaceous Glance Conglomerate,
- Early Cretaceous Bisbee Group (Glance Conglomerate, Willow Canyon Formation, Apache Canyon Formation, and Shellenberger Canyon Formation),
- Late Cretaceous Fort Crittenden Formation and Salero Group,
- Late Cretaceous Mt. Wrightson Formation, and
- Late Cretaceous igneous rocks (Madera Canyon, Elephant Head, Mt. Fagan).

Mesozoic sedimentary rocks consist of continental and shallow marine conglomerate, sandstone, and siltstone units that overlie the older units. Some volcanic (andesitic) rocks are interbedded with the Mesozoic sedimentary sequence. A Lower Cretaceous andesite flow ranging in width from a few tens of feet to several hundred feet wide overlies siltstone of the Lower Cretaceous Willow Canyon Formation. Shale and laminated mudstone of the Lower Cretaceous Apache Canyon Formation and Upper Cretaceous Rhyolite of Mt. Fagan and Rhyolite megabreccia (ash-flow tuff) overlie the Willow Canyon Formation (CNF, 2011).

Triassic-Jurassic Periods

Gardner Canyon Formation. The Gardner Canyon Formation is of Triassic to Jurassic age. In the Mount Fagan quadrangle, it consists of a heterolithic assemblage of dark red mudstone or slate, volcaniclastic sandstone, and conglomerate, with sparse volcanics, including a dacitic ash-flow tuff (Ferguson et al., 2001). In the Helvetia quadrangle, the Gardner Canyon Formation consists of maroon to tan metasiltstone and sparse fine metasandstone, with some resistant quartzite beds and local conglomerate (Ferguson et al., 2009).

In the Rosemont area, the Gardner Canyon Formation is 1,148 feet thick. The Gardner Canyon Formation includes a diverse range of mudstone, sandstone, conglomerate, and limestone strata, with minor ash-flow tuff units (Ferguson et al., 2001; 2009). The units are predominantly reddish, with minor amounts of green mudstone. The upper and lower contacts of the formation are low-angle faults (Ferguson et al., 2001).

Cretaceous Period Sedimentary Rocks

The Lower Cretaceous Bisbee Group in the Santa Rita Mountains includes the Glance Conglomerate, Willow Canyon, Apache Canyon, Shellenberger Canyon, and Turney Ranch formations. The Bisbee Group conglomerate, shale, and arkose formations are widespread throughout the Santa Rita Mountains. The units have been correlated with respect to geologic time, <u>with no implication of lateral continuity</u>, to similar units and stratigraphic sequences in the nearby San Cayetano, Patagonia, and Whetstone mountains, and Canelo Hills (Drewes, 1981, Plate 1). In the Mule, Swisshelm, Huachuca, and Peloncillo mountains to the south and southeast, Early Cretaceous marine limestone beds and coral reefs were deposited during the northernmost incursion of the Bisbee basin portion of the Chihuahua trough. These limestones are not present or not well developed in the area of the Santa Rita Mountains.

At the time of their deposition in the Early Cretaceous, the landforms in the Rosemont area consisted of upland areas with local highs (no deposition, only erosion), mountain-front alluvial fans shedding sediments into fault-bounded basins, braided streams draining the local valleys and ranges, and the limited incursion of a marine sea that was the Bisbee basin embayment of the much larger epicontinental Western Seaway. The Bisbee basin is an intracratonic backarc basin[4] that joined with the Chihuahua trough to the southeast (Klute, 1987). Farther south and east of the Rosemont area, non-marine conglomerate, redbed sandstone/siltstone, and shale formations of the Morita Formation and Cintura Formation underlie and overlie, respectively, a thick unit of marine Mural Limestone that indicates the transgression and regression of a regional marine incursion.

Klute's work (1987) on sandstone and arkose facies within the northwestern and southeastern part of the Bisbee basin indicates that different depositional regimes existed within the basin, and that the sediment was supplied from different sources. This condition created numerous lateral facies changes and variations in depositional thickness. Structural and sedimentological barriers trapped debris and hindered through-flowing sediment transport down the basin axis toward the Chihuahua trough. The units are not regionally interconnected today primarily as a result of subsequent, locally important faulting and erosion that have

[4] A backarc basin is a depression that forms landward of a volcanic arc (mountain range) formed during subduction. The basin is lined with trapped sediment eroding from the volcanic arc and plate (craton) interior.

isolated the ranges into what are informally called "sky islands." This structural setting is illustrated in Drewes' regional geology surface map (Drewes et al., 2002), a portion of which is presented in Figure 3.

Glance Conglomerate. In the Santa Rita Mountains, the Upper Jurassic and/or Lower Cretaceous Glance Conglomerate consists of conglomerate at the base of the Bisbee Group. In some areas, such as the Empire Mountains, the Glance consists of several facies that sequentially record clasts shed from the uplift of adjacent mountains, first exposing the Paleozoic limestones, then the underlying granite (Bilodeau, 1978). In the Mount Fagan quadrangle, the Glance Conglomerate consists of massive to very thick-bedded, clast-supported conglomerate (Ferguson et al., 2001). In the Helvetia quadrangle, the Glance Conglomerate also consists of a wide variety of clast types that are pebble to cobble sized, subangular to subrounded (Ferguson et al., 2009).

In the Rosemont area, the Upper Jurassic and/or Lower Cretaceous Glance Conglomerate is 0–980 feet thick. It consists of massive- to very thick-bedded, clast-supported conglomerate containing pebbles, cobbles, and local boulders that reflect the composition of underlying Proterozoic through Permian rocks. The basal contact is an angular unconformity. Within the Rosemont area, the Glance is a white, fine- to medium-grained, marble conglomerate (CNF, 2011).

Willow Canyon Formation. In the Whetstone and Santa Rita mountains, the Willow Canyon Formation gradationally overlies the Glance Conglomerate and consists of alternating, arkosic sandstone and reddish-brown to greenish-gray siltstone, which becomes coarser grained to the west. Its thickness varies from 0 to 570 feet (0-170 m) in the Whetstone Mountains, 0 to 3,000 feet (0-900 m) in the Empire Mountains, and is up to 2,200 feet (660 m) in the Santa Rita Mountains. In the Mount Fagan quadrangle, the Willow Canyon, Apache Canyon, and Shellenberger Canyon formations are undifferentiated. They consist of thin- to thick-bedded, argillaceous, feldspathic sandstone or arkose interbedded with olive gray shale and mudstone, typically containing pyrite (Ferguson et al., 2001). In the Helvetia quadrangle, the Willow Canyon Formation is also fine- to coarse-grained arkosic sandstone interbedded with dark olive gray to maroon to dark purple mudstone (Ferguson et al., 2009).

In the Rosemont area, the Lower Cretaceous Willow Canyon Formation is 7,200 feet (2,200 m) thick. It consists of a succession of medium- to coarse-grained, feldspathic sandstone (typically arkosic arenite) and argillaceous sandstone with some vuggy, silty mudstone. A distinctive interval of volcaniclastic pebble-cobble conglomerate is present near the middle of the unit, below a sequence of mafic lava flows. The conglomerate contains as much as 70% mafic and intermediate-composition, porphyritic, igneous clasts, including clasts of chert and quartzose sandstone. Sandstone throughout the formation is cross stratified to plane-bedded, typically medium to thick bedded. Weak to moderate propylitic alteration has been identified in the Willow Canyon Formation in the Rosemont area (CNF, 2011).

Apache Canyon Formation. In the Whetstone and Santa Rita Mountains, the Apache Canyon Formation gradationally overlies the Willow Canyon Formation and consists of interbedded, thin, dark-gray, silty limestones; dark-gray shales; calcareous siltstones; and arkosic sandstones. In the Helvetia quadrangle, the Apache Canyon Formation consists of thin-bedded, arkosic sandstone, mudstone, dark gray micritic limestone, and pebbly sandstone (Ferguson et al., 2009).

In the Rosemont area, the Lower Cretaceous Apache Canyon Formation is ~1,300 feet (>400 m) thick. It consists of medium- to thick-bedded sequences of shale and laminated silty mudstone with subordinate interbeds of thin-bedded, dark gray, fetid, micritic limestone and feldspathic sandstone (Johnson and Ferguson, 2007).

Turney Ranch Formation. In the Mount Fagan quadrangle, the Turney Ranch Formation consists of medium- to thick-bedded quartz sandstone interbedded with tin- to medium-bedded reddish, silty mudstone and shale (Ferguson et al., 2001). In the Rosemont area, the Lower Cretaceous Turney Ranch Formation is 3,280 feet thick. It consists of alternating layers of sandstone and mudstone that range from 16 to 160 feet thick and typically are reddish in color (Ferguson 2009; Ferguson et al., 2001). The sandstone commonly is cross stratified, and the sandstone units generally are fractured (Ferguson et al., 2009). The formation is not described in the Helvetia quadrangle (Ferguson et al., 2009).

The upper unit of the Bisbee Group, the Shellenberger Canyon Formation is not described in the Mount Fagan quadrangle (Ferguson et al., 2001), but is described in the Helvetia quadrangle. There it is described as arkosic sandstone and mudstone capped by a limestone unit. The Shellenberger Formation is not described in the Rosemont area (Johnson and Ferguson, 2007).

Horquilla Limestone (Pennsylvanian)

Mineralized Epitaph Formation (Permian)

Willow Canyon Formation (Lower Cretaceous)

Apache Canyon Formation (Lower Cretaceous)

Source: C. Hoag photographs, July 2012

Figure 7 Photographs of Paleozoic and Cretaceous sedimentary rocks in the Rosemont area

Fort Crittenden Formation. In the Huachuca and Santa Rita mountains, the Upper Cretaceous Fort Crittenden Formation is as much as 5,500 feet (1,650 m) thick and consists of red and brown conglomerate and sandstone, fossiliferous black shale, and a rhyolitic tuff that is intercalated with the upper beds.

In the Rosemont area, the Upper Cretaceous Fort Crittenden Formation is 4,920 feet thick. It consists dominantly of clastic strata ranging in size from pebbly sandstone to cobble- and boulder-clast-sized conglomerate and volcanic beds (Ferguson, 2009; Ferguson et al., 2001). Riley (2004) reports the formation thickness is approximately 4,900 feet thick (CNF, 2011).

Salero Formation. The Salero Formation overlies the Fort Crittenden Formation and plutonic rocks in the southern Santa Rita Mountains. The Salero consists of dacitic volcanic rocks that grade upward and laterally into arkosic fanglomerate, quartzite, and redbeds up to 2,500 feet thick (Drewes, 1971). The Salero Formation also contains a widespread, pyroclastic, andesitic breccia that contains numerous exotic blocks and is disconformably overlain by the welded tuff member of the Salero Formation (Drewes, 1971).

The Salero Formation is combined with the Fort Crittenden Formation – Salero Group undifferentiated in the Helvetia quadrangle (Ferguson et al., 2009). It is not noted in the Rosemont area.

Late Cretaceous Period Volcanic and Plutonic Rocks

Late Cretaceous (early Laramide orogeny) volcanic rocks in the Santa Rita Mountains include the Mt. Fagan Rhyolite in the Mount Fagan quadrangle and the Mt. Wrightston Formation in the Helvetia quadrangle. Numerous Late Cretaceous, monzo-dioritic to quartz monzonitic plutons that are locally associated with lead-zinc-silver mineralization are present in the Santa Rita Mountains. These include the Elephant Head Quartz Monzonite and Josephine Canyon Diorite in the Santa Rita Mountains (Drewes, 1976) and the Sycamore stock in the Empire Mountains (Finnell, 1971).

Mt. Fagan Rhyolite. In the Mount Fagan quadrangle, the Rhyolite of Mount Fagan consists of crystal-rich, densely welded, rhyolite ash-glow tuff containing phenocrysts of quartz, plagioclase, potassium feldspar, and biotite. The monolithic megabreccia units at Mount Fagan are characterized by very large (over 100 m wide) megaclasts (Ferguson et al., 2001). These exotic blocks in volcanics are typical of the Late Cretaceous caldera complexes throughout southern Arizona (Keith and Wilt, 1986). This unit is similar to the megabreccia units in the Salero Formation.

The Mt. Fagan Rhyolite megabreccia and the Mt. Fagan Rhyolite occur in the Rosemont area. The megabreccia clasts consist mostly of feldspathic sandstone and argillite of the Bisbee Group, along with subordinate fine-grained andesite. The Mt. Fagan Rhyolite is a phenocrysts-rich ash-flow tuff containing phenocrysts of quartz, feldspar, and biotite in a welded to nonwelded, light colored matrix (Johnson and Ferguson, 2007).

Mount Wrightson Formation. The Mount Wrightson Formation may be environment- and time-equivalent to the Rhyolite of Mount Fagan. In the Helvetia quadrangle, the Mt. Wrightson Formation contains sandstone and tuff, rhyolite lava, megabreccia, and ash-flow tuff (Ferguson et al., 2009). It was not mentioned in the Rosemont area geologic descriptions.

Corona de Tucson stock. In the Mount Fagan quadrangle, the Corona de Tucson stock consists of quartz monzonite dated at 75.3 and 75.5 Ma (Marvin et al., 1973).

Empire Mountains stock. In the Mount Fagan quadrangle, the Empire Mountains stock is a medium-grained granodiorite and is slightly more felsic in its core (Ferguson et al., 2009). It was dated at 71.9 Ma (Marvin et al., 1973).

Madera Canyon pluton. In the Helvetia quadrangle, the Madera Canyon pluton is of Late Cretaceous age. It contains potassium feldspar phenocrysts in a fine- to medium-grained groundmass of plagioclase, potassium-feldspar, quartz, and some mafic minerals (Ferguson et al., 2009).

Elephant Head Quartz Monzonite. In the Helvetia quadrangle, the Elephant Head pluton is a leucocratic syenogranite containing potassium-feldspar, plagioclase, quartz, biotite, and magnetite. The texture ranges from fine-grained porphyritic to medium-grained quartz monzonite (Ferguson et al., 2009). It was dated at 69.9 to 70.8 Ma (Marvin et al., 1973).

3.4 Cenozoic Era

Cenozoic volcanic and plutonic rocks include the Early Tertiary (middle Laramide orogeny) calc-alkalic plutons associated with the porphyry copper deposits. These include the andesite porphyry and quartz-feldspar porphyry in the Rosemont area, the Quartz porphyry in the Mount Fagan quadrangle, and the feldspar porphyry, Helvetia granite, and quartz-feldspar porphyry in the Helvetia quadrangle.

Cenozoic sedimentary units include consolidated and unconsolidated (loose) conglomerate, colluvium, talus debris, and alluvium. Conglomerates are composed of clay- to boulder-sized grains eroded from older rocks that are at the surface nearby at the time at which the conglomerate is deposited. The Gila Conglomerate ranges in age from Pliocene to Miocene (Johnson and Ferguson, 2007) and the thickness varies locally. This unit contains a wide range of weathered rocks, ranging from quartz monzonite through carbonate and older silt. The matrix contains calcite and is notably alkaline, similar to contemporary soils in the adjacent basins (CNF, 2011).

Tertiary Period

Andesite porphyry. In the Rosemont area, the Paleogene–Upper Cretaceous andesite porphyry is a strongly altered, fragmental, fine-grained plagioclase porphyritic andesite or intrusive porphyry. Elliptical outcrops are located along the margin of the Mt. Fagan caldera (Johnson and Ferguson, 2007).

Quartz-feldspar porphyry. In the Rosemont area, the Paleogene–Upper Cretaceous quartz-feldspar porphyry consists of a light gray to pink felsic porphyry dikes and stocks containing 8% to 15% phenocrysts of quartz, and as much as 25% feldspar and 1% to 2% biotite (Johnson and Ferguson, 2007).

Skarn. In the Rosemont area, the Paleogene–Upper Cretaceous skarn is the result of alteration by the Paleogene intrusions. Metasomatic alteration (influx of hydrothermal solutions rich in silica, aluminum, iron, and magnesium) and replacement of carbonate units, has produced calc-silicate rocks and hornfels in association with sulfide and oxide copper mineralization (skarn is synonymous with the term tactite). Oxidized skarn contains gangue minerals characterized by intense iron-oxide and local clay alteration (CNF, 2011).

Gila Conglomerate. The Gila Conglomerate of Pliocene?–Miocene age is over 655 feet. It consists of light brown, medium- to thick-bedded, conglomerate, pebbly sandstone, and sandstone with a calcareous matrix. The clasts are subangular to round. The composition includes sedimentary, volcanic, and igneous clasts representing the composition of rock types found in upslope areas. Granite/quartz monzonite composes as much 70% of the clasts. Granitoid clasts are absent in the upper Pleistocene terrace gravels, so this is an important diagnostic characteristic of the Gila Conglomerate (CNF, 2011).

Quaternary Period

Older Alluvium of Late Pleistocene? age is 13–40 feet thick in the Rosemont area. Weakly consolidated gravel terraces consist of medium- to thick-bedded, sandy, pebble-cobble gravel with rare boulders, derived from upslope or upstream units. The deposits are generally incised between 13 and 40 feet, locally forming cliffs and ledges as much as 10 feet high (Johnson and Ferguson, 2007).

Colluvium and Talus of Holocene–Late Pleistocene age has a variable, unmeasured thickness. It consists of unconsolidated deposits and debris consisting of subangular to angular pebbles, cobbles, and boulders derived from upslope units (Johnson and Ferguson, 2007).

Younger Alluvium of Holocene–Late Pleistocene is 0–10 feet thick. Alluvium was deposited in streams and washes that are actively being incised, are generally less than 10 feet deep, and are locally vegetated (Johnson and Ferguson, 2007).

4 Structure

The northern Santa Rita Mountains are bounded on the south by the Sawmill Canyon fault zone. This is a major wrench fault system that has been active throughout the Mesozoic and Cenozoic. This fault zone is inherited from Proterozoic tectonics and reactivated in the Mesozoic and Cenozoic (Drewes, 1981; Titley, 1976; Bassett and Busby, 2005).

Folding and faulting (shown on the geologic map of the Rosemont area on Figure 4) occurred in several intervals of geological time. Most host rocks at Rosemont dip steeply (approximately 55–65 degrees) to the east. Numerous faulting episodes occurred during the various orogenies that established mountain-front faults via normal, thrust, reverse, detachment, and strike-slip faults. During these active orogenic episodes, stratigraphic beds were folded and tilted and mountains or paleo-topographic highs were created. These faults, folds, and areas of nondeposition prevent direct lateral continuity between correlative units found in adjacent ranges. Thus, correlations between mountain ranges do not prove direct, hydraulic or other interconnections between the same units within mountain ranges or across basins (CNF, 2011).

The principal faults in the Rosemont area include the nearly horizontal Low Angle fault (formerly called the Flat fault) and the later north-striking Backbone fault system. The Low Angle fault places mostly Mesozoic sedimentary rocks over the older Paleozoic units. The Low Angle fault separates the upper, weakly mineralized oxide zone from the underlying, strongly mineralized, sulfide zone. Oxidized and supergene copper mineralization above the Low Angle fault appear to be well developed in the Mesozoic-age andesitic rocks (M3 Engineering and Technology Corporation, 2012; CNF, 2011).

The post-mineral Backbone fault system defines the western boundary of the ore deposit and separates the mineralized, Paleozoic limestone units on the east from the Proterozoic granodiorite and lower Paleozoic quartzite on the west. Post-mineral features partially delimit the defined resource, dividing the deposit into major structural blocks with contrasting intensities of mineralization. The north-trending, steeply dipping

Backbone Fault juxtaposes marginally mineralized Precambrian granodiorite and Lower Paleozoic quartzite and limestone to the west against a block of younger, well-mineralized Paleozoic limestone units to the east. The bulk of the copper sulfide resource is contained in the eastern block of the Backbone fault (CNF, 2011).

Structurally overlying the sulfide resource is a block of Mesozoic sedimentary and volcanic rocks that contains copper oxide mineralization. These two blocks are separated by the shallowly dipping Low Angle fault. Other post-mineral features include a deep, gravel-filled Tertiary paleochannel on the south side of the deposit and significant thickness of Cretaceous and Tertiary volcaniclastic material to the northeast of the deposit. The bulk of the sulfide resource on the east side of the Backbone Fault and below the Low Angle fault is hosted in a steeply east-dipping package of Paleozoic-age sedimentary rocks (M3, 2012).

No evidence exists in the deposit area of recent fault activity that cross cuts Quaternary or Holocene talus, colluvium, alluvial fan or terrace gravels. These alluvial formations typically mask the underlying, older fault contacts where faults are present (Ferguson et al., 2009; CNF, 2011; M3, 2012).

5 Mineralization

The Santa Rita Mountains include two major types of Laramide ore deposits – the earlier lead-zinc-silver mineralization of approximately 85-75 Ma and the later porphyry copper mineralization of approximately 65 – 56 Ma. Keith (1974, 1975) describes individual mines in the Santa Rita Mountains. Additional distinctions and historical production information are in Keith et al. (1983). The Rosemont porphyry copper deposit is located in the Helvetia-Rosemont mining district in the northern Santa Rita Mountains.

5.1 Early Laramide (Lead-Zinc-Silver Deposits – Tyndall Mining District)

Massive volcanic centers were built during the early Laramide phase (80-70 Ma) in southern Arizona. These large volcanoes explosively erupted large volumes of rhyolitic ash and andesitic volcanic rocks. Then the volcanic structures collapsed into the void left by the erupted ash leaving huge calderas, such as the Cat Mountain Rhyolite west of Tucson. 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 the early Laramide lead-zinc-silver mineralization in the Empire and Santa Rita Mountains are the Empire, Tyndall, Old Baldy, and Salero mining districts. Examples of mining districts that produced excellent silver and lead minerals include those in the southern Santa Rita Mountains and Tombstone area. The Glove mine on the western side of the Santa Rita Mountains is an example of the early Laramide lead-zinc-silver deposits. The underground mine was developed to extract mineralization from crystal-lined vugs and cavities in tubular cave shoots in the Pennsylvanian Horquilla Limestone (Olson, 1966).

5.2 Middle Laramide (Porphyry Copper Deposits – Helvetia-Rosemont Mining District)

Large porphyry copper deposits were created during the middle Laramide orogenic phase (approximately 67-55 Ma) during the early Tertiary period. These disseminated copper deposits are associated with porphyritic (coarse crystals in a fine-grained ground mass) granitic (granodiorite to quartz monzonite) intrusions (Keith and Wilt, 1986). Examples of the Laramide porphyry copper deposits include mines in the Tucson area: Pima district (Twin Buttes, Sierrita-Esperanza, Rosemont, and Mission-Pima mines) south of Tucson, the Silver Bell mine northwest of Tucson, and the old Ajo mine west of Tucson. These mining districts commonly have other historic mines in a bulls-eye pattern outward from the copper-rich core in this sequence: copper-zinc, zinc-lead-silver-gold, to silver-manganese at the outer zones. Skarn deposits (contact metamorphic deposits with garnet and calc-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 (Rasmussen, 2012).

Examples of the middle Laramide porphyry copper mineralization in the Santa Rita Mountains are the Cuprite, Helvetia, Rosemont, Box Canyon, Greaterville, Jackson. To the south of the Santa Rita Mountains in the San Cayetano and Patagonia Mountains middle Laramide porphyry copper mineralization occurs in the Red Mountain, Thunder Mountain, Washington Camp, Palmetto, Patagonia, and Harshaw, and Querces mining districts.

Rosemont Deposit

Mineralization from the Laramide orogeny is typically associated with intrusions of granite-like rocks, though it also occurs less frequently in adjacent, older sedimentary rocks. Unlike most other porphyry copper deposits in the area, the Rosemont mineralization occurred primarily in metasomatized limestone (skarn) and other sedimentary rocks rather than in a granitic or related intrusive rock. Most of the oxide mineralization occurs in the Mesozoic sedimentary and volcanic rocks (CNF, 2011).

Skarn Deposits

The Rosemont deposit is typical of the porphyry/skarn copper class of deposits. Similar to many other southwestern USA deposits in this class, Rosemont consists of broad-scale skarn mineralization developed in Paleozoic-aged carbonate sedimentary rocks adjacent to their contact with porphyritic quartz latite or quartz monzonite intrusions. Broadly disseminated sulfide mineralization occurs primarily in the altered Paleozoic skarn units and to a lesser extent in the altered intrusive units. Near surface weathering has resulted in the oxidation of the sulfides in the overlying Mesozoic units (M3, 2012).

The Rosemont deposit primarily is a garnet-diopside skarn (of the type that formed by metasomatism of Paleozoic sedimentary rocks of Cambrian, Devonian, Mississippian, Pennsylvanian, and Permian age), with some oxide deposits in clastic rocks of Late Jurassic-Early Cretaceous age. The Rosemont deposit formed in response to emplacement of quartz latite to quartz monzonite stocks in Laramide time (approximately 56 million years ago). Calcium-silicate minerals replaced and overprinted the limestone and dolomitic host units with a new mineral assemblage consisting of sulfides and quartz, garnet, diopside, wollastonite, anhydrite and other gangue minerals. The resulting rock is typically harder, denser, and less porous than the original host rocks. In areas of contact metamorphism, marble was formed from the more pure carbonate rock types, while the more siliceous, silty rocks were altered to hornfels (CNF, 2011).

History

Mineral exploration in the Santa Rita Mountains dates from the mid-1800s. By 1880, small underground mines and smelters had been established in the area. By the 1880s, production from mines on both sides of the Santa Rita Mountains supported the construction and operation of the Columbia Smelter at Helvetia on the western side, and the Rosemont Smelter in the Rosemont mining district on the eastern side (CNF, 2011). The Helvetia Mining District and the Rosemont mining district, located on the west and east flanks of the northern Santa Rita Mountains, respectively, were established in 1880 (CNF, 2011).

The first significant study of mineral deposits and geology of the region was by Schrader (1915). That investigation is a detailed analysis of the presence of gold, silver, copper, lead, zinc, tungsten, and molybdenum in fissure veins and replacement or contact-metamorphic deposits and contains a detailed geological map of the area. Starting in the 1950s, work in the area began to delineate larger, disseminated deposits such as the Rosemont ore deposit through extensive drilling programs by various companies. By the time most production had ceased in 1951, the area had produced approximately 227,300 tons of ore containing 17.3 million pounds of copper, 1.1 million pounds of zinc, and 181,000 ounces of silver (CNF, 2011).

Although most production ceased in 1951, exploration continued in the northern Santa Rita Mountains. The Narragansett Mine, a mine with copper, silver, zinc, lead, gold mineralization, continued to operate until 1961. It produced more than 90,000 tons of ore materials averaging more than 4% copper and 0.5 ounce of silver per ton (Mindat, 2010). Banner Mining Company, which had acquired most of the claims in the area by the late 1950s, drilled the discovery hole into the Rosemont deposit (CNF, 2011).

The Rosemont ore deposit was documented as a major porphyry copper deposit in 1963 by Anaconda Mining Company. Anaconda Mining Company acquired the property in 1963 and carried out an extensive exploration program that identified Rosemont as a major porphyry copper deposit. In 1973, Anaconda joined with AMAX, forming the Anamax partnership. The partnership lasted until 1986, when Anaconda was dissolved, at which time the Rosemont and Peach-Elgin properties were sold to a real estate company. ASARCO purchased the property in 1988, began engineering studies on the Rosemont property, and drilled 12 diamond drill holes. In 2004, ASARCO sold the entire property to real estate interests (CNF, 2011).

Drilling continued sporadically over the next four decades, culminating in the most recent drilling programs conducted by Augusta Resource Corporation from 2005 through 2008 (WLR Consulting, 2007; Daffron et al., 2007)) and through early 2012 (Augusta Resource Corporation, 2012a, 2012b). In 2005, Augusta Resource acquired the Rosemont property, continued delineation of the Rosemont deposit through sampling and drilling, and in 2007 submitted a preliminary Mine Plan of Operations to the Forest Service (CNF, 2011).

Ore Minerals

The copper mineralization of the Rosemont deposit is primarily sulfide with a cap of oxide mineralization. The copper sulfide-bearing materials in potentially economic concentrations consist approximately of Horquilla

Limestone (46%), Earp Formation (17%), Colina Limestone (15%), Epitaph Formation (9%), Escabrosa Limestone (4%), and other (9%), which includes quartz monzonite porphyry and other formations (Williamson, 2012). The Mesozoic host rocks are the Willow Canyon Formation and the Glance Conglomerate, which are predominantly arkosic siltstone, sandstone, and conglomerate and contain "exotic" copper oxide mineralization. The Willow Canyon Formation also includes mafic or andesitic flows, which host minor oxide mineralization (CNF, 2011).

Sulfide mineralization at Rosemont consists primarily of chalcopyrite, pyrite, and molybdenite in calc-silicate replaced limestone hosts (skarn). These minerals occur as veinlets and disseminations in the Paleozoic, garnet-diopside skarn, and associated marble and hornfels. The sulfide minerals are accompanied by quartz, amphibole, serpentine, and chlorite alteration. Silver is minor but economically important. Silver mineralization is associated with the primary copper mineralization in the Paleozoic rocks. Trace amounts of gold are anticipated to be recovered; however, anticipated recovery rates are not expected to be significant (CNF, 2011).

Supergene sulfides include chalcocite and bornite. Silver mineralization is associated with primary copper sulfide mineralization. Oxide mineralization includes chrysocolla, malachite, azurite, tenorite, and other oxide-silicate minerals in fractured, iron-stained surface outcrops.

Copper oxide mineralization results from weathering of the primary copper sulfide minerals. The oxide mineralization occurs in the upper part of the ore deposit, primarily in the Mesozoic limestone, siltstone, sandstone, conglomerate, and andesite, and also is present in Paleozoic rocks near the surface on the west side of the deposit. Copper oxide mineralization primarily includes copper-bearing limonite, chrysocolla, tenorite, malachite, and azurite. Minor amounts of enriched chalcocite and associated native copper mineralization are found in and beneath the oxide mineralization (CNF, 2011).

The copper oxide-bearing host rocks consist primarily of Willow Canyon arkose (50%), quartz monzonite porphyry (15%), and quartz latite porphyry and andesite (35%). The copper oxide mineralization is extractable with dilute sulfuric acid on a heap leach facility, but will not be processed per updated feasibility results published in August 2012 (Augusta Resource Corporation, 2012b; M3, 2012).

Extensive drilling has identified mineralization to a depth of at least 2,000 feet below the surface (M3, 2012). The degree (concentration) of mineralization diminishes to the south. The copper mineralization appears to extend northward amid complex faulting and eastward beneath an increasingly thick Mesozoic cover, as observed in drill cores (CNF, 2011).

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