Caves in the Northern Santa Rita Mountains, Arizona

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1 Introduction

Caves, cracks, and dissolution features have long been identified in the northern Santa Rita Mountains of Santa Cruz and Pima Counties, Arizona. These range from small features that do not meet or barely meet the definition of a cave to three significant caves that are greater than one mile each in surveyed length. One other notable cave (Glove Mine Cave) was intercepted and exploited by historic mining operations. These four caves are located in two regions at the base of the Santa Rita Mountains – along the western flank in the Montosa Canyon area (16 miles west-southwest of the proposed Rosemont Copper operation) and the eastern flank in the Sawmill Canyon area approximately 8 miles south of the Rosemont project (Figure 1).

During the public comment period for the Rosemont Draft Environmental Impact Statement (EIS), public comments were provided to Coronado National Forest (CNF) that expressed concern about potential impacts to caves in the Santa Rita Mountains. The questions and concerns primarily focused on the effects of groundwater withdrawal on the known caves and cave speleothems, and the potential that caves may be present in the areas of disturbance for the proposed project. SRK Consulting was asked to summarize what is known about the caves in the Santa Ritas including location, geology, types of speleothems, wet/dry characteristics, and source of water present. This paper excerpts scientific information provided to CNF during their technical reviews and preparation of the Final EIS. The information and conclusions presented are the authors' opinions only and do not reflect the views of the Arizona Geological Society, CNF, Rosemont Copper Company, or any other entity; endorsement of the proposed project is not given or implied by the authors of this paper.

2 General Comments on Cave Formation and Features

A cave is any natural cavity, fissure, or tube that is human-sized or larger and which extends past the twilight zone into total darkness (Hill and Forti (1997). Palmer (1991, 2000) defines a cave as a humanly enterable, underground void or space without respect to geologic formations. Caves have been known to form in limestone and evaporite beds, granite, and volcanic rocks including basaltic lava tubes. The origin and morphology of limestone caves has been extensively studied by Palmer who did fieldwork in 500 caves supplemented by published data on several thousand other caves.

Caves can be formed by karst and non-karst processes. Landforms formed by karst processes are noted for their distinctive characteristics including closed depressions, sinkholes, disrupted surface drainages, disappearing streams, and underground drainage systems spanning miles in extent. Active karst and paleokarst topography is found in the carbonate units of the Colorado Plateau region in northern Arizona and in the Transition Zone south of the Mogollon Rim (Stringfield and others, 1974). Paleokarst features (karst topography, subsurface drainage, lateritic residuum) may have developed in southeastern Arizona for a brief period in Late Mississippian time in the Escabrosa Limestone below the lower red clastic member of the Pennsylvanian Black Prince Limestone (Ross, 1973). Active karst systems are not present in southeastern Arizona so will not be discussed further as a mechanism for cave formation in the Santa Rita Mountains.

2.1 Non-Karst Cave Types

In southern Arizona, the vast majority caves were formed by non-karst processes rather than by the dissolution and groundwater flow processes associated with karst topography. The caves have formed in clastic and carbonate formations, as well as extrusive and intrusive igneous rocks. A number of caves in the region are associated with dissolution processes accompanying formation of metallic ore deposits. All of the known caves in the Santa Rita Mountains were formed by non-karst processes that operated several to many geologic epochs prior to the present. The caves and pieces of caves are relict features exposed by structural deformation and subsequent mountain-front erosion and retreat. Brief explanations of the three non-karst types of caves are provided below.

Oxidation subsidence caves are formed over deposits containing sulfide minerals. Volume reduction in the deposit occurs when sulfides are oxidized through exposure to meteoric water and oxygen. According to

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Wisser (1927), "the effects of oxidation shrinkage resemble those of stoping. As the ore, its walls and its floor lose volume during oxidation, the unsupported roof fails, and by the dropping out of blocks from its center, begins to take the form of an arch or dome. Successive doming cracks, one above the other, form curved shells above the ore, and as subsidence proceeds, the cracks open wider and wider and the shells successively fail and break into blocks, which fall from the roof and make a jumble of fragments, large and small, like the filling of a caved stope." This entire process is mechanical in nature and may result in subsidence cracks and concentric fractures that stope their way to the surface or are that exposed at the surface owing to weathering.

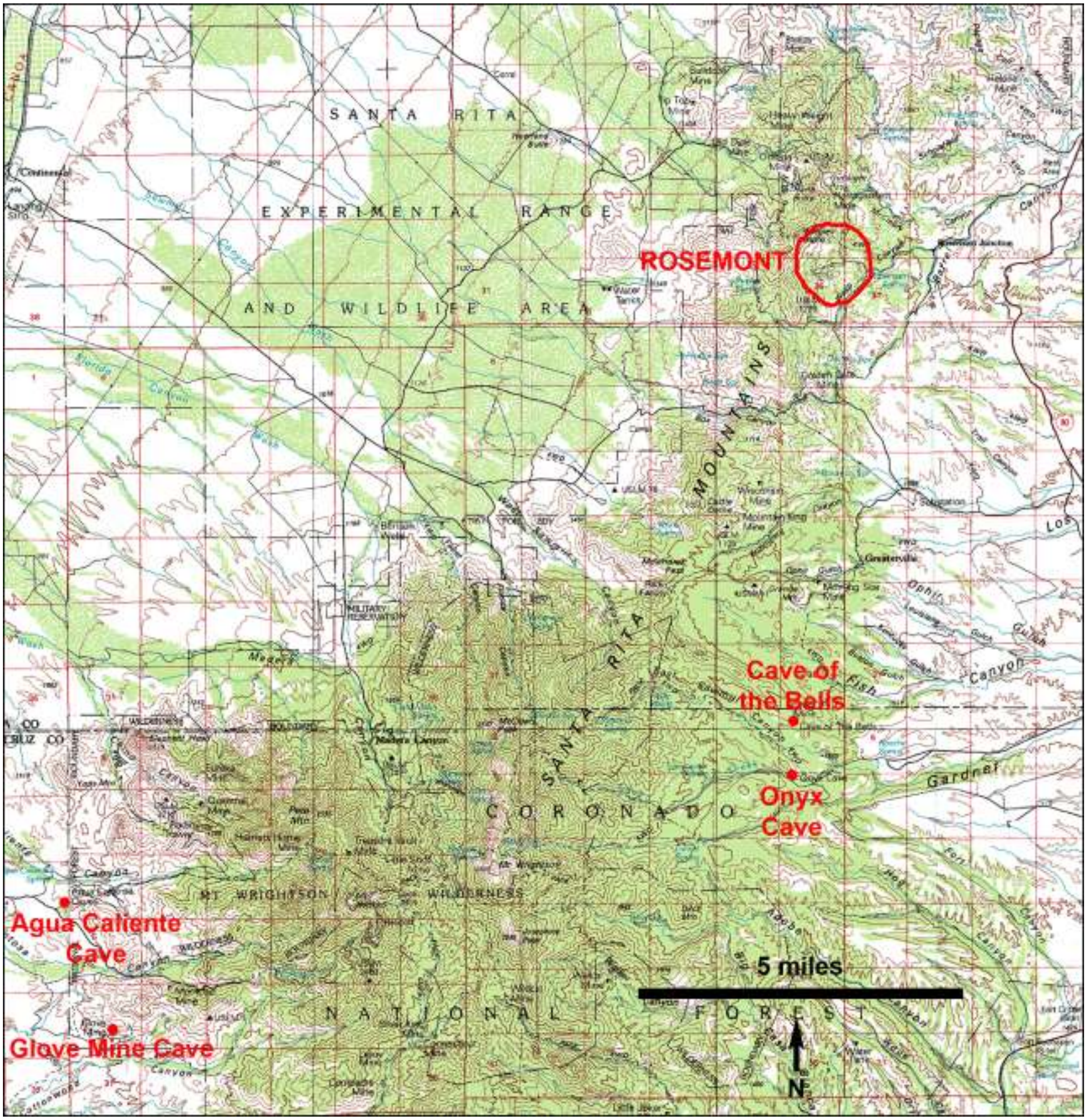


Figure 1 Location of notable caves in the northern Santa Rita Mountains (U.S.G.S. 30x60 minute Ft. Huachuca quadrangle). Red circle shows approximate outline of proposed pit.

The most numerous and best known caves associated with oxidation subsidence include the caves of the Warren mining district in Cochise County. This process is illustrated in three figures from Edward Wisser's (1927) classic treatment of the subject at Bisbee as shown in Figure 2 for massive-bedded limestone beds and in Figure 3 for thin-bedded limestone beds. While the cave types below can form with or without economic concentration of minerals, oxidation subsidence caves require large volumes of associated sulfide minerals to provide enough volume voids to initiate the spalling of the overhead rock. Thus, oxidation subsidence caves are typically associated with high concentrations (historically or currently economic) of metals.

Hydrothermal dissolution caves can form by the chemical interaction, mixing, and cooling of rising thermal fluids with overlying carbonate formations. The thermal fluids can be generated as a result of geothermal activity, volcanic or magmatic activity, or the emplacement of an intrusive body with associated metallic minerals. The dissolution and fissure widening occurs owing to the inverse relationship between calcite solubility and temperature, even at constant CO_2 levels (Palmer, 1991). However, the equilibrium P_{CO2} of rising water is usually greater than that of the atmosphere of the cave into which it emerges. The process of precipitation of calcite is usually limited to depths within a few meters of the water table. Palmer found that this effect rapidly diminishes with depth and gives way to bedrock dissolution.

According to Palmer (1991) "decreasing temperature in rising thermal waters can maintain or create solutional aggressiveness," but that "only under the most favorable conditions can dissolution by cooling of thermal water [*alone*] produce caves of traversable size". Palmer states that most thermal cave origin probably requires the presence of hypogenic acids or mixing with meteoric water from nearby sources.

An example of the hydrothermal dissolution mechanism in the Santa Ritas is seen in Cave of the Bells (Figure 1), which has strong evidence of a hydrothermal dissolution origin, but which lacks associated metallic mineralization.

Hypogenic dissolution caves are those formed by aggressive dissolution that has been produced at depth, independent of acid sources at or near the surface. Caves formed by these processes show little or no genetic relationship to patterns of groundwater recharge from the overlying surface. Common hypogenic agents include sulfuric acid produced by the oxidation of sulfides, renewed aggressiveness caused by the cooling of ascending water, the mixing of waters from depth that encountered meteoric water, and acids caused by digestion of hydrocarbons by bacteria (Palmer, 2000). These types of caves are not always related to mineral deposits. They also form in relation to thrust or detachment faulting where H_2S-bearing brines ascend the faults, mix with descending meteoric water, thereby creating sulfuric acid, and dissolve rock along the fault (Figure 4).

All three of these types of caves may be found in conjunction with mineralized deposits, but not all caves formed by these processes have economic concentrations of metals. In the Santa Rita Mountains, Onyx Cave and Agua Caliente Cave are the best examples of hypogenic dissolution cave development without economic metallic sulfide mineralization. Other examples of hypogenic dissolution caves in Pima County that are related to hypogenic processes along detachment faults include Colossal Cave (Peachey, 2000), Arkenstone Cave, and La Tetera Cave in the Rincon Mountains, and possibly the vugs or pockets associated with the San Xavier underground mine south of Tucson near the Mission mine. An example of ore-related hypogenic dissolution caves are the pipes at the Glove mine where acidic fluids from the oxidation of sulfide minerals ascended along permeable zones and leached the limestone (Olson, 1966). Hydrothermal and hypogenic processes of cave formation are gradational and often work in concert with one another.

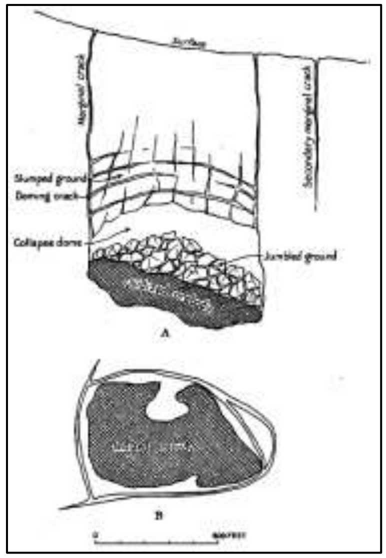


Figure 2 Subsidence features in massive limestone, near surface (Wisser, 1927, Fig. 5)

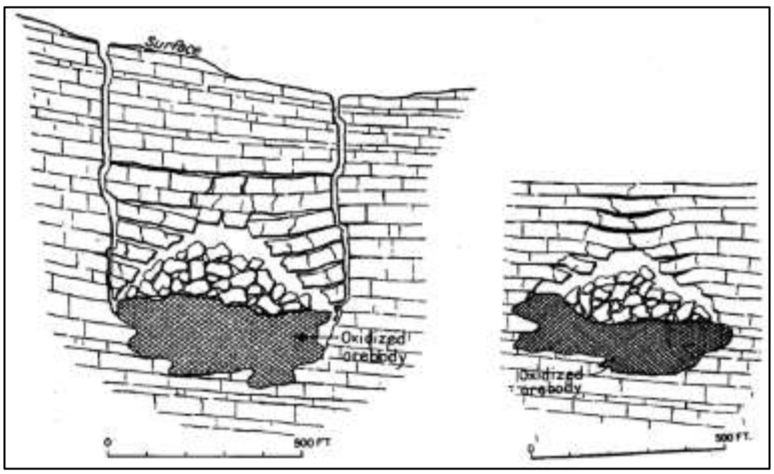


Figure 3 Subsidence features in thin-bedded limestone, near surface (left) and at depth (right) (Wisser, 1927, Figs. 7, 8)

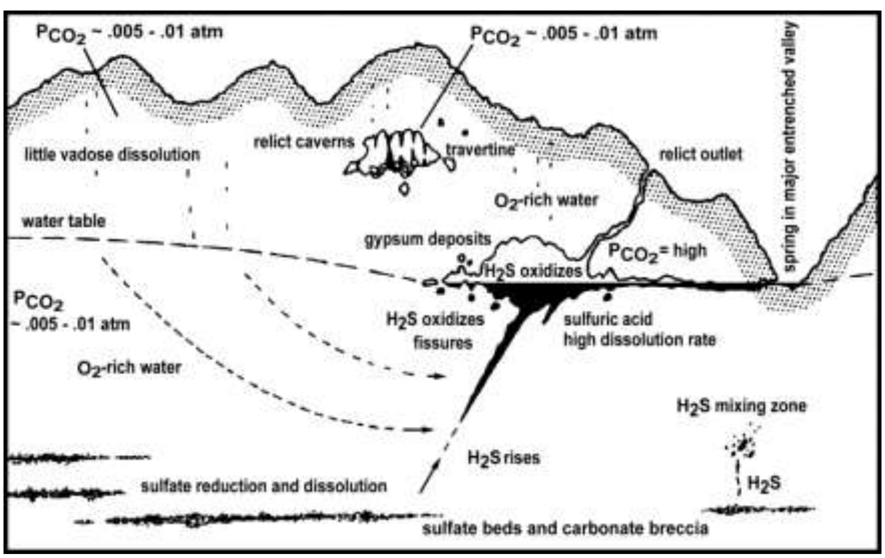


Figure 4 Origin and typical distribution of caves formed by oxidation of hydrogen sulfide (Palmer, 2000)

2.2 Moisture Characteristics – Wet versus Dry Caves

The term "wet cave" versus "dry cave" is a relative term that lacks any formal definition with respect to quantifiable parameters, such as volume of water, depth of water in shallow depressions or flooded passageways, duration of the presence of the water (seasonality), and water chemistry. The term is of descriptive use in comparing general cave characteristics in caves found in a similar regional environment and may not be directly comparable to the term as used by speleologists in another part of the country. Speleologists in the southeastern U.S. may call a cave "dry" or parts of a cave "dry" because the moisture content in a portion of the cave is much lower than found elsewhere in the same cave. For instance, caves in the southeast Unites States, such as Mammoth Cave in Kentucky, have continuous free-flowing water on a year-round basis. Mammoth Cave has five distinct levels of developed cave passages in which the upper levels have drip formations only and are drier than the lowest level, which has continuous stream flow. In contrast to these types of caves, the majority of caves in southeastern Arizona would be considered to be dry based on a comparison of humidity values, water volume, flow duration, and other parameters.

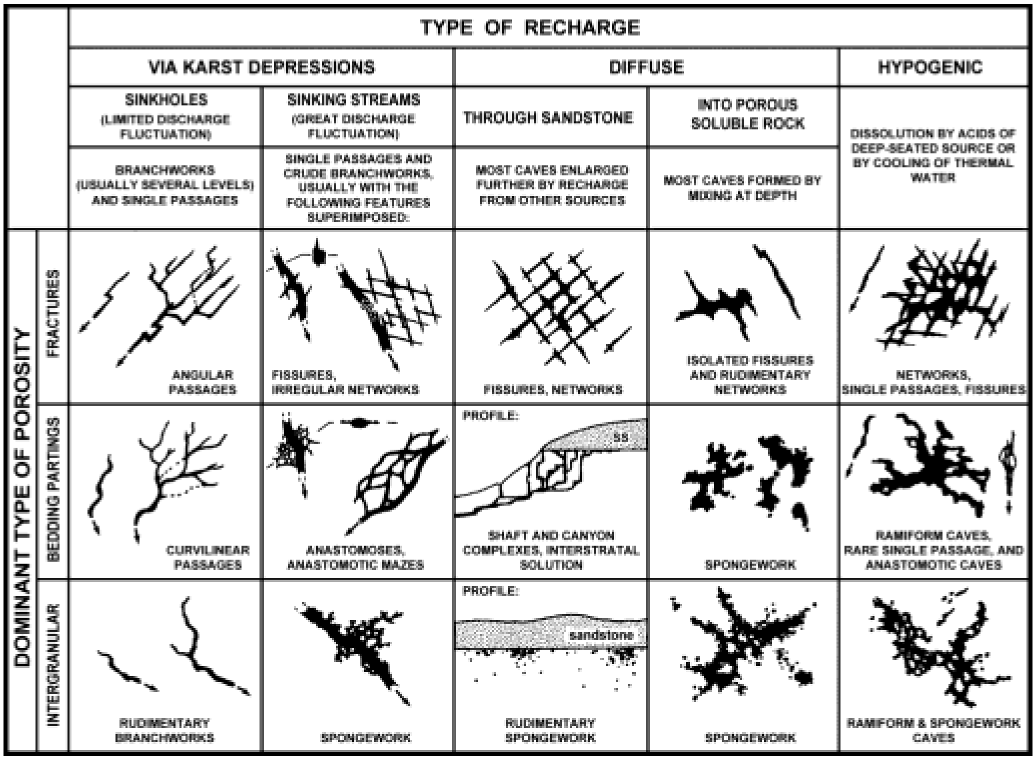
Most caves in southeastern Arizona are seasonally wet to some degree, but the quantity of water is relatively limited, dissipates quickly, is sensitive to drought conditions, and does not typically occur in a free-flowing stream. Local southeastern Arizona caves such as Peppersauce, Colossal, Scroll, and Agua Caliente have been designated by speleologists as "dry" caves even though they all collect seasonal meteoric water and may have wet areas within their passageways for brief periods in a given year. Kartchner Caverns and Onyx Cave have both been designated as "wet" caves, even though drought conditions can cause large portions of these caves to be completely dry during extended periods in a given year. Kartchner Caverns would be considered to be a "dry" cave in comparison with cave systems in the southeastern U.S. Even in southeastern Arizona, the dry and wet caves mentioned above are on a gradational scale and are designated in a subjective manner according to local convention.

Wet caves and the presence of "living" (i.e. actively growing) speleothems is an association made by the public, but the correlation of the presence of moisture and active speleothem development is not always true. Evidence at Cave of the Bells (discussed below in Section 3) suggests that the speleothems in this cave have had several periods of inactivity or calcite non-deposition, the latest of which has lasted approximately 11,000 years despite the current wet conditions within this cave.

2.3 Recharge Mechanisms for Cave Water

Caves in active karst systems have recharge mechanisms from sources on or near the surface that reach the caves through conduits that are usually formed along structural elements, such as joints, fractures, and faults. These underground streams discharge as surface flow in springs or streams. Figure 5 illustrates the dominant types of porosity and recharge for karst and non-karst caves.

Caves in southeastern Arizona are relict caves (see Figure 4) that are no longer associated with their original source of fluids. They are not connected with groundwater and are located above the current water table. The water sources are meteoric water that primarily enters through primary porosity (pore space between grains) or fractures in the form of drip water. Most of the caves have seasonal pools that collect in the deepest part of the cave along passages that are developed along high angle structures. These pools fluctuate with a distinct lag time of possibly several months that follows precipitation events on the surface. Locally in the Santa Rita Mountains, the winter precipitation seems to be the dominant seasonal inputs of water to the caves (Wagner and others, 2010). Pools in Onyx and Cave of the Bells are known to be perennial, but their water levels fluctuate on a seasonal basis and there are no stream inputs.



Source: Palmer (2000, Section 3.4, Figure 10). Summary of cave patterns and their relationship to types of recharge and porosity. Maps are plan views unless otherwise noted and are generalized to represent typical caves in each category. Many exhibit rudimentary forms, multiple stages of development, or combinations of more than one type. Individual passages differ in specific layout according to the local physical setting.

Figure 5 Cave patterns, porosity, and types of recharge mechanisms in cave formation process (Palmer, 2000)

3 Caves in the Santa Rita Mountains

Caves, cracks, fissures, and dissolution features have long been identified in the northern Santa Rita Mountains. These range from small features that do not meet or barely meet the definition of a cave (a human-enterable cavity that extends past the twilight zone into total darkness) to three significant caves that are greater than one mile each in surveyed length. One other notable cave (Glove Mine Cave) was intercepted and exploited by historic mining operations. These four caves are located in two limited regions at the base of the Santa Rita Mountains – along the western flank in the Montosa Canyon area (16 miles west-southwest of the proposed Rosemont Copper operation) and the eastern flank in the Sawmill Canyon area approximately 8 miles south of the Rosemont project. Numerous fissures and a few small named and unnamed caves occur in Sawmill Canyon, such as Hidden Cave and Greenhouse Cave, but will not be described in detail here.

A brief summary of characteristics of the enterable cave features in the Santa Rita Mountains is provided in Table 1 including general characteristics, geologic formation, and the local source of water in the cave. The caves listed in Table 1 are known for the complexity of their passageways, unpredictable branching, and great irregularity of profiles (i.e. abrupt changes of 20 ft to 100 ft in elevation that coincide with changes in passage dimensions). All of these characteristics indicate an origin other than the smooth flow of phreatic water or vadose zone stream courses. They contain bodies of massive endogenic clay and lack clastic stream deposits, indicating that free-flowing water is not responsible for their formation. Furthermore, the irregularities in their profiles indicate a lack of leveling (cut and fill) by stream erosion, had it been present.

The morphology of three of the caves (Glove Mine Cave, Agua Caliente, and COB) suggests that a combination of ramiform cave development and network fissure widening was responsible for their creation, according to definitions provided by Palmer (1991; 2000). In contrast, Onyx Cave is dominantly a ramiform structure. The morphology of all of these caves indicates their origin is most likely to be hypogenic or a combination of hypogenic and hydrothermal.

Onyx Cave received National Natural Landmark status for its abundance and variety of calcite speleothems. The lesser known Agua Caliente Cave is much smaller and drier, but the system has nearly an equal variety of calcite speleothems in comparison with Onyx Cave. Located a short distance from Agua Caliente Cave, the cave at the Glove Mine lacks current exposure of a variety of calcite speleothems because the cave itself was highly mineralized and the ore materials were excavated from the solution cavities in the Horquilla Limestone beginning in 1907. In addition, collectors through the present time have removed high-quality wulfenite and associated gangue mineral specimens.

Figure 6 presents the location of the notable caves with respect to the location of the Rosemont project. This map also shows a contour indicating the extent of the 5-ft projected groundwater drawdown during the post-closure period (Montgomery and Associates, 2009). The drawdown is modeled to occur in response to pit dewatering during mine operations and the continued flow inwards towards the pit post-closure because the open pit is projected to be a terminal sink in perpetuity.

Table 1 Summary of known significant caves in the Santa Rita Mountains

Name	**Location in Santa Ritas**	**General Characteristics**	**Local Source of Water Present Today in the Cave**
Glove Mine (Cave)	West flank (Montosa Canyon Area)	Ramiform[1], high angle, epigenic caves lined with calcite and copper, lead, molybdenum mineralization. Formation: Pennsylvanian Horquilla Limestone (Drewes, 1972b, Plate 2)	Meteoric water (Olson, 1966)
Agua Caliente Cave	West flank (Montosa Canyon area)	Combination of ramiform/network fissure cave; passageways with closed loops on disparate elevations. Hottest cave known in the U.S. (known to exceed 103˚F owing to: (1) multiple entrances on a south-facing slope, (2) chimney flow ventilation of hot summer air, and (3) dark surface patina on the limestone close to the surface, which absorbs heat and radiates it into the cave passages located close to ground surface. Formation: Permian Concha Limestone (Drewes, 1972b, Plate 2)	Meteoric water; hill is denuded so water can enter directly and ephemeral flow in the cave has been noted rarely. (Peachey, oral commun., 2012)
Onyx Cave	Eastern flank (Sawmill Canyon area)	Ramiform cave in a 0.5 mile extent of Permian Rainvalley Formation. Cave consists of one major loop with passageway branches going downward to both the inside and outside of the loop. One passage (Mud Shoots) intercepts the level of surface flow outside the cave. Cave is above the water table and is dominated by drip water collection. Hydrothermal (high temperature) onyx was commercially mined at the Onyx Mine #1 and Onyx Mine #2 excavations, located 350 ft and 600 ft from the cave entrance, respectively. Formally designated a *National Natural Landmark* in 1969. Formation: Permian Rain Valley Formation (Drewes, 1972b, Plate 1; Brod, 2010)	Meteoric water. Drip water collecting in passage bottom has been noted to overflow to the surface in the drainage below the cave. (Brod, 2010; Truebe, 2009; 2012)
Cave of the Bells	Eastern flank (Sawmill Canyon area)	Combination ramiform and high-angle network fissure cave (0.25 mile long) in complexly folded and faulted Permian Epitaph Dolomite and Colina Limestone, overlain by impermeable Triassic siltstone of the Gardner Canyon Formation (Brod, 2010). Predominantly large solutionally enlarged fractures with drip water. Water is warmer than the air temperature in the cave implying potential hydrothermal influence. Formation: Permian Epitaph Formation (Drewes, 1972b, Plate 1; Brod, 2010)	Meteoric water with $\delta^{18}O$ isotope records back to 53,000 years bp. Water source in the cave was attributed to winter precipitation according to isotopic analysis. (Wagner and others, 2010; Truebe and others, 2010; Murray, 2012).

Source: Compiled by the authors, SRK, 2012

Note: [1]Ramiform caves resemble ink blot patterns in plan with irregular rooms and galleries that wander three-dimensionally with branches extending outward from the main development areas. Passage interconnections are common, producing a continuous gradation with spongework and network caves. Abrupt variations in gradient and cross section are typical.

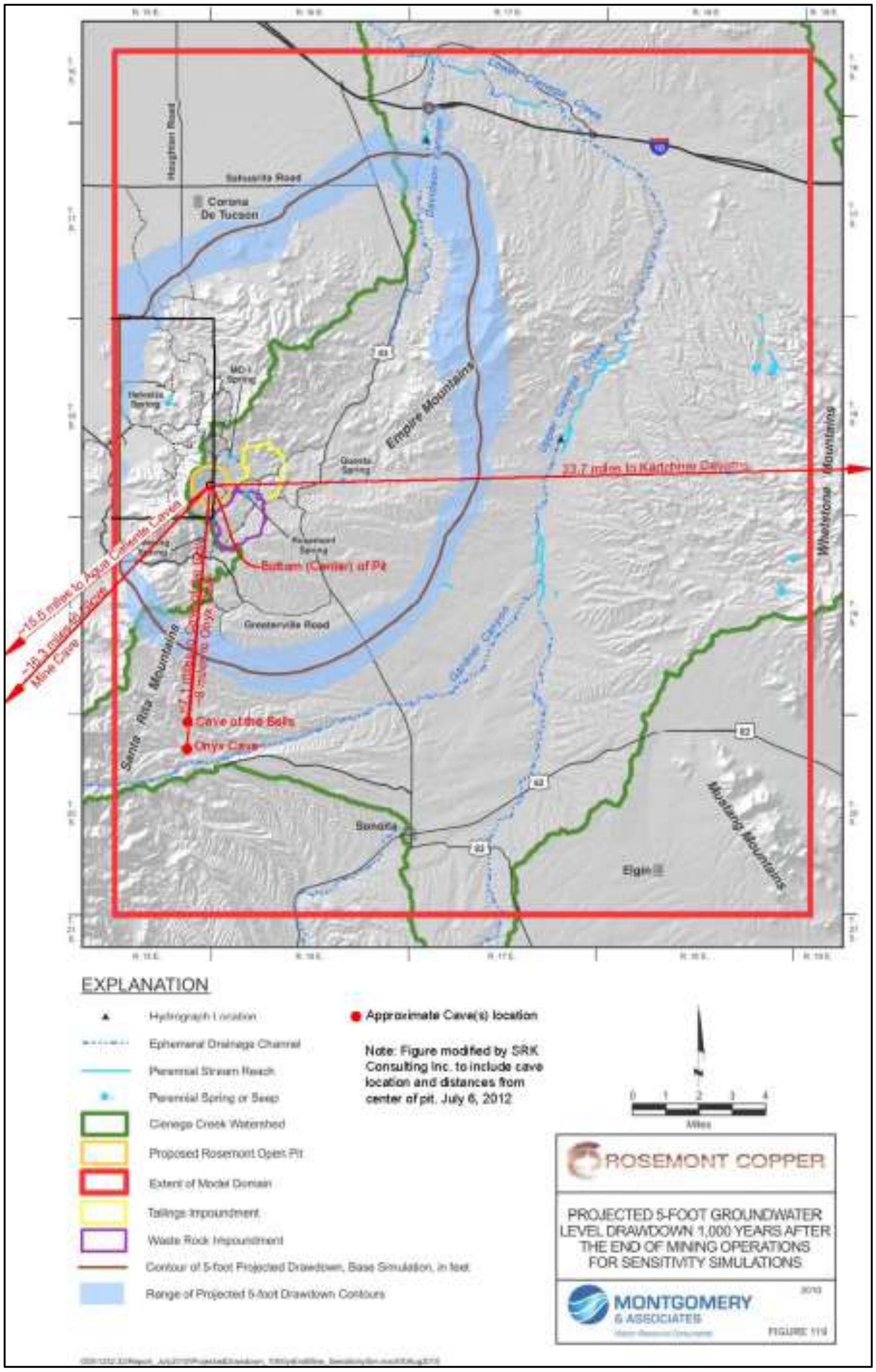


Figure 6 Location of significant cave resources in the Santa Rita Mountains (modified from M&A 2009 figure showing steady state (1,000 years) groundwater drawdown contours)

3.1 Cave of the Bells

Cave of the Bells (COB), located approximately 7.1 miles south-southwest of the Rosemont project, is relatively lacking in abundance and variety of speleothems in comparison with the other three caves (Figure 7). It is well-known, however, for its higher temperature form of calcium carbonate—large anthodites of aragonite (i.e. crystal forms that are tree-like in appearance). Aragonite is the high-temperature polymorph of calcite and forms in caves at temperatures greater than 56˚F. COB is formed in Permian Epitaph Formation.

COB is the only cave of interest where detailed scientific research concerning water has been undertaken. It is the site of on-going paleoclimate investigations by researchers at the University of Arizona and other institutions. A recent publication (Wagner and others, 2010) and a Master of Science thesis (Murray, 2012) links moisture variability in the southwestern United States (as documented by $\delta^{18}O$ analyses on a stalagmite from COB) to abrupt glacial climate change. Wagner's team was able to demonstrate high correlation of COB data with the $\delta^{18}O$ records in other regions of the United States and in the Greenland ice cores. This research, as well as current research by doctoral student Sarah Truebe, University of Arizona (Truebe and others, 2010), suggests that the source of nearly all water entering COB over a period of 53,000 years before present (bp) has been derived from winter precipitation rather than from groundwater flow. In addition, the COB research shows there are several hiatus periods in stalagmite growth ranging from 300 to 1,500 years in length, and that there appears to have been no stalagmite growth since before the end of the Wisconsin glaciation (11,000 bp) (Wagner and others, 2010).

Additional details and observations of the stratigraphy, mineralization, structure, and the presence of water in the caves in Sawmill Canyon and the adjacent terrain are presented in a report contributed to the Arizona Geological Survey by local speleologist Lang Brod[4] (2010). His field investigations occurred over decades, and his water-related observations are not identified by date. Lang recorded the presence, however, of small pools of water at COB at a depth of approximately 270 feet below the single entrance of the cave, which is located at 5,480 ft above mean sea level. He attributed the pools to meteoric drip water. The water levels in the pools rise seasonably from inputs of drip water and fall during intervening dry periods and/or droughts. The offset lag time between winter precipitation and rises in the pools has not been precisely documented owing to lack of meteorological instrumentation in the cave, but it is well known anecdotally by local cave enthusiasts including the co-author Peachey.

Figure 7 View of speleothems within Cave of the Bells (photos sourced from internet)

3.2 Onyx Cave

Onyx Cave, located approximately 8 miles south-southwest of the Rosemont project, is noted for its variety and numbers of speleothems. Onyx Cave is similar to COB in that it also contains seasonally fluctuating pools at depth with lag times between precipitation and the rise in water noted in the pools. Brod (2010) notes "Groundwater enters Onyx Cave through cracks and fissures in the overlying limestone, forming drips and small pools." A significant feature of Onyx Cave indicates the source of water in this cave is also meteoric. Unlike COB where the entrance is less than 15 ft above the closest stream course, the entrance to Onyx Cave is more than 280 ft above the level of nearby Cave Creek (Figure 8). The entrance is located near the crest of a narrow, elongate ridge of Permian Rain Valley Formation that overlooks the south side of the Sawmill Canyon fault zone. The pool level in Onyx Cave is seasonally congruent with the flow level noted in Cave Creek at the southeast base of Onyx Hill. Brod (2010) indicates the end of the surveyed passageways in Onyx Cave is about 20 meters above the base of Onyx Hill. In the early 1960s (~1960–1963), local speleologists with UAAC Grotto chapter of the National Speleologist Society (NSS) dye-traced the water in the terminal pool (lowest pool in the cave) known as the "Mud Chutes." The dye reported to a stream outside the southeast portion of Onyx Hill at the limit of carbonate outcrops in the channel of Cave Creek (Peachey, oral commun., 2012). Observations of local cavers and speleologists indicate that the level of water in the Mud Chutes pool has only reached a level high enough to exit the cave a few time in the last 50 years (Peachey, oral commun., 2012).

[4] Lang Brod is a fellow of The National Speleological Society (NSS) and former member of the NSS Board of Directors. He has 40 years of experience mapping caves in southeastern Arizona. Prior to coming to Arizona he was a founding member of the Missouri Speleological Survey, spending 8 years mapping caves and karst in Missouri.

During the last three years, S. Truebe, doctoral student at The University of Arizona, has been monitoring cave temperature, cave humidity, cave CO_2, drip rates, and outside rainfall with help of volunteers from Escabrosa Grotto, a chapter of the National Speleological Society. Her results yet to be published in a peer-reviewed journal, but she informally reports in the Escabrosa Grotto Desert Caver publication that Onyx Cave is fed by rainwater, and that even without chemical analysis, the drip water can be classified as "seasonal" with pulsed response to strong winter and monsoonal rain (Truebe, 2009; 2012). Although the cave drip water and speleothems have not yet been studied with chemical and isotope analyses, it is highly likely based on the monitoring work completed to date, that the drip water moving through this cave system is meteoric water that falls on the hill immediately above it and infiltrates through the jointed limestone beds.

Figure 8 Left image shows a view of Onyx Cave ridge looking northward from Hidden Cave Trail. Red arrow indicates location of cave entrance on skyline 90 ft below crest on southwest side of hill (Peachey, 2012). Right image shows human and large stalagmite in dry pool in Onyx Cave dry pool (Smith, 1966)

Note: Left image shows water droplets hanging from new growth on several broken stalactites caused by human traffic dating to the 1950s. Field of view is approximately 3.5 in.

Note: Right image shows the beginning of the growth of an offset soda straw from the tip of a stalactite. It shows the characteristic growth of thin "teeth" of calcite crystal just underneath the surface of the periphery of the skin of the water drop, in a downward growing circle that sequentially extends the length of the soda straw over time. The helectites apparently often get their start from tiny openings that have been formed by the incomplete joins along the edges between competing crystal tabs. With a lowering of the water supply rate, calcite crystals may grow inside of a soda straw and stop it up. When that happens the tube may become pressurized by the water that has been backed up by the stoppage. Then, it can be forced out and through these incomplete spots in the wall of the straw to form helectites. Note the rare "beaded helectite" that has grown up at an angle about 45 degrees from the top of the cluster on the left and above the tip. Field of view is approximately 2 in

Figure 9 New crystal growth and water droplets in Onyx Cave (Peachey, 2012)

3.3 Glove Mine Cave

The Glove Mine Cave is located approximately 16.3 miles west-southwest of the Rosemont project on the west side of the Santa Rita Mountains. Insufficient information exists to comment on the source and status of water at this privately owned cave. This natural fissure or cave feature in Pennsylvanian Horquilla Limestone was historically excavated by the shaft, drifts, and levels of an underground mining operation. Co-author Hoag visited the mine in the mid-1980s on a one-day mineral collecting visit, and the subsurface levels and drifts were dry more than 100-200 ft below the shaft collar (ground surface).

The Glove mine is a small, oxide, lead-silver-zinc deposit that was located in 1907 and worked intermittently from 1922 through 1972 in the Tyndall mining district on the southwestern flank of the Santa Rita Mountains. Extensive solution of the limestone and deep oxidation concentrated cerussite, anglesite, wulfenite, and smithsonite in the etched caverns as sand carbonate ore (Keith, 1975).

The mine is located within an isolated block of Paleozoic and Cretaceous sediments intruded by Early Laramide[5] quartz monzonite and latite porphyry sills. The mineralization and metamorphosed limestone beds (marble) are cut by a series of tight faults. In contrast to the Rosemont area, the contact metamorphic effects at the Glove Mine from the igneous sills are relatively minor. No continuous tactite zone has been developed and only two minor areas of silication containing epidote and garnet were noted (Olson, 1966).

Olson (1966) reports "Solution by groundwater, aided by acids from the oxidation of the sulfides, especially in the zones of brecciation developed at fault intersections, has produced cavernous pipes." These mineralized coalescing pipes were "developed along zones of permeability formed by faults and fault intersections within the favorable limestone (Figure 10). Ore fluids ascending along these permeable zones replaced the limestone, forming stringers and bands of massive sulfide and some minor sulfide disseminations. Later acids from oxidation of the sulfides further leached the limestone, forming a complicated system of caverns controlled largely by the original permeable zones and the sulfide pipes. As the caverns enlarged, they were filled with the oxidation products of the sulfide minerals, along with quantities of wad, calcite, gypsum, and minor silica. Boulders of limestone and marble that collapsed from the backs during the leaching of the cavern are scattered throughout the cavern fill". In general, the more pure limestone units were favorable to ore deposition, and intensely silicified limestone and siltstone were unfavorable hosts (Olson, 1966).

"The oxide portion of the Glove mine is wholly above the water table. During periods of high seasonal rainfall, surface runoff is captured by open fractures and cavernous zones in the limestone, which provide for entry and downward percolation of groundwater" (Olson, 1966).

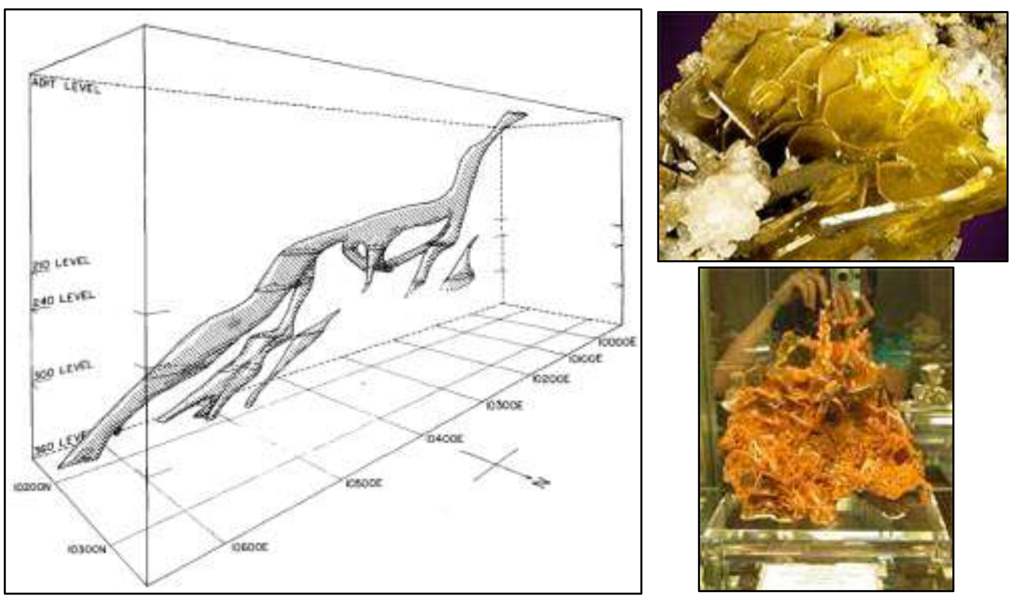


Figure 10 Cave tunnels in the Glove mine cave, (Olson, 1966, Fig. 5) and wulfenite mineralization formed in cavernous pipes and vugs

[5] The lead-zinc-silver system of the Tyndall mining district and related quartz monzonite found at the Glove Mine is probably near 70 million years old (Ma) assuming it is related to the Elephant Head quartz monzonite dated at 70.8 Ma (Marvin and others, 1973). In contrast, the Helvetia quartz latite near Rosemont was dated at 55.2 Ma (Marvin and others, 1973) and is a porphyry copper system.

3.4 Agua Caliente Cave

Much can be relayed about the condition of Agua Caliente Cave[6] because it has been visited almost continuously from the initial discovery in the late 1950s until recent years, when it was gated for the first time by a private owner. The cave is located approximately 15.5 miles west-southwest of the Rosemont project on the west side of the mountains. The plan of the cave consists of the parts of five distinct loops that are crudely stacked one above the next in an open fan array such that the upper loops are nearly horizontal while those below are successively inclined to a greater and greater extent. To one side of the set of loops, the loops are nearly tangential to one another; in the opposite direction they open down and away from one another. The loops are irregular in shape, discontinuous, and, around their circumferences they are, seemingly randomly, interconnected by inclined to vertical shafts. Three of the four upper loops are much more incomplete than the lower two loops. Two of the loops are much greater in circumference than the others—one being almost complete in its circuit while the circuit of other forms a dashed line of unequal length dashes. The result is entry into a three-dimensional maze for cave explorers.

Agua Caliente Cave has the label of being the hottest cave in the United States. During the heat of the Sonoran Desert summer, this cave has been known to record temperatures in excess of 100ºF. The cave is located underneath a hill whose south face is almost entirely devoid of vegetation. The Permian Concha Limestone units that the cave has developed within are very dark in coloration and have been highly fractured. In addition, the cave has several entrances that are located at different elevations. Finally, the passages of the upper levels of the cave are located just beneath the surface of the hill such that summer heating of the exposed, dark limestone beds radiates directly into the air of the cave passages. The result is that hot air in the summer can enter an entrance low on the hill and rise through the cave passages to exit at another entrance that is higher on the hill. This ‘chimney effect’ combines with the direct radiation of heat from the exposed dark, heat-absorbing limestone that thinly roofs the upper levels of the cave to create overwhelming heat levels. With such high seasonal air temperatures, very little water can remain in the ephemeral cave pools from year to year.

Many cavers, especially those who are members of local caving organizations, keep cave logs or journals of their caving activities for recording conditions that are relevant to expediting their cave travel, technical requirements (i.e. rigging points for rope drops, the lengths of ropes required, times needed to reach destinations, etc.), as well as for recording their exploits. Review of these records kept by co-author Peachey from 1970 through 1990 shows a 20-year intermittent but downward trend in the volume and duration of water in the three small pools known to collect seasonal moisture in Agua Caliente cave.

In contrast to the generally dry conditions, there have also been several records by credible observers of “streams of water cascading into cave passages.” Agua Caliente Cave is located in a hill of largely exposed bedrock that is surrounded by low-capacity desert washes. It does not have any known underground connections to sources of water to contribute to its moisture level. In rare random events, a thunderstorm cell will remain stationary directly over the hill. Intense precipitation can occur in a short period of time onto the surface of the barren hill such that it enters open fractures that intercept the cave passages close to the surface with enough volume to make “waterfalls” in one of the driest caves in North America.

3.5 Dissolution Features

Numerous non-cave forming dissolution and fracture-widening features can be found in the Santa Rita Mountains wherever carbonate rock occurs. Such joints produce shallow surface corrosion features that do not connect to local groundwater or generate a cave feature. An example of shallow corkscrew solution holes exposed in the walls of an open-cut prospect pit near Sycamore Canyon is shown in Figure 11. The surface corrosion extends approximately 5 ft below the existing ground surface and appears to be guided by joint surfaces. One can also note the occurrence of float that may indicate the presence of historic, eroded speleothem-like features. These features, such as shown in Figure 12, have cave popcorn-like growths and botryoidal calcite coralloid polyps that could form either aerially in the vadose zone or subaerially in the phreatic conditions in a cave. They may also have formed in bedding partings, hydrothermal dissolution fractures, or subsidence cavities that are all related to mineralization processes. In the area where the Figure 11 float was found, there was no evidence of relict (fossil) caves. It should also be noted that whitish to beige-colored, earthy to powdery caliche is ubiquitous in the northern Santa Rita Mountains. It appears to drape the slopes at the bedrock-soil interface in this area in layers and lenses as thick as 2 ft. The exposures of caliche

[6] Note the cave is designated “Agua Caliente Caves” on topographic maps owing to the fact there are multiple cave entrances. There is only one cave so this feature will be called “Agua Caliente Cave”.

layers and caliche-cemented fragments are visible in road cuts and are draping natural outcrops and bare areas on the slopes.

Figure 11 Fracture-guided dissolution features exposed in a wall of a prospect pit (SRK, 2012)

Figure 12 Cross section (left) and plan view (right) of distal terminations of calcite crystal growths found in cave-like cobble float on outcrops of Horquilla Formation (SRK, 2012)

3.6 Cave Forming Units in Santa Rita Mountains

While the Mississippian Escabrosa Limestone is widely known as a "cave- former" in Sonora, Mexico and southeastern Arizona (including Kartchner Caverns), none of the known caves in the Santa Rita Mountains have formed in this unit. In the areas surrounding the largest caves as discussed in this section—Onyx, COB, Agua Caliente, and Glove Mine Cave—Escabrosa limestone has either not been mapped or has been mapped at a distant location such that it has not been involved in local speleogenesis. As referenced in Table 1, the dominant “cave-formers” in the Santa Rita Mountains are Pennsylvanian Horquilla Limestone and limestone beds in the Permian Epitaph, Concha, and Rain Valley formations.

In the Rosemont project area, mineralized Horquilla Limestone and Epitaph Formation comprise approximately 46 percent and 11 percent of the sulfide ore, respectively (Geochemical Solutions, 2012, Table 1). While the presence of a potential unknown cave in the Horquilla or Epitaph cannot be ruled out, the mineralized carbonate units have been partially or completely transformed to skarn so are less amenable to cave development or cave preservation in comparison with unmineralized limestone (as discussed below). Mineralized Concha Limestone is a minor ore component in the proposed open pit. The Rain Valley Formation does not occur within the footprint of the proposed pit, plant site, or tailings and waste rock storage areas.

3.7 Meteoric Water, not Groundwater, in the Santa Rita Caves

Evidence to date, including modern speleological observations since the early 1960s and recent isotopic research at COB (Wagner and others, 2010), indicates the caves in the Santa Rita Mountains are isolated features that are not connected to regional groundwater flow systems. The physical geometry of the caves indicates they are typically found in isolated limestone blocks or occurrences that are today well above the local water tables as indicated by data from nearby wells and physical evidence underground. The caves are relict features that are not interconnected with each other or with the local water table. The COB evidence suggests that meteoric water, notably winter precipitation, is the dominant water source for the caves in the Santa Rita Mountains (Brod, 2010; Wagner and others, 2010).

In the authors' opinion, groundwater withdrawals related to pit dewatering and continued post-closure drawdown are unlikely to affect the wet or dry characteristics of any of the Santa Rita Mountains caves or their speleothems because these caves are not connected to the local or regional groundwater table. The caves, cave water sources, and cave speleothems will be most affected by drought, local climate change, erosion, and human entry rather than by changes to the local groundwater table.

3.8 Lack of Cave Features Documented to Date at Rosemont Project

Extensive work in the Rosemont project area – including historic and current mapping, prospecting and soil/rock surface sampling, 18 miles of geophysical surveys, biological and cultural resources surveys, roadwork, and drilling – has not discovered any cave resources in the project area. Drilling density is currently spaced approximately one drillhole every 250 ft, which allows good penetration of representative local host and overburden formations, especially in the area immediately overlying the deposit. Decades of field visits and searches by local speleologists, cavers, and other recreationalists have also been unsuccessful in locating cave resources in the project area.

Intensive exploration activities (mapping, surface sampling, drilling on approximate 250-ft centers) by Rosemont Copper Company (Cornoyer, 2011) have not revealed evidence of caves or karst formation in the project area. The lack of cave resources was attributed to the presence of skarn that overprinted and replaced the original host limestone in the immediate deposit area. Skarn results when high-temperature hydrothermal fluids derived from the granitic magmas and containing silica, iron, magnesium, aluminum, and other constituents interact and mix with the carbonate rocks in a contact zone such that a new suite of minerals is created (i.e. quartz, garnet, epidote, magnetite, hematite, pyroxene, wollastonite, actinolite, etc.). The resulting rock suite has characteristics that differ in texture, hardness, density, porosity, hydraulic connectivity, and mineral composition from the original host formations. Pre-skarn voids and open fissures in the host limestone, if they exist, can be filled and plugged off with the deposition of minerals or isolated through the intrusion of the mineralizing intrusion. Although voids and vugs may still occur, the mineralization and metasomatism associated with the formation of the deposit replaces the original limestone hosts with minerals less amenable to dissolution, as well as overprinting much of the fossil record in the host carbonate rocks.

Some may ask if other southeastern Arizona caves associated with mineral deposits are analogs for what could be found at the Rosemont deposit. The caves associated with the San Xavier mine, the Bisbee mines, and the Glove mine are in limestone or marble without calc-silicate minerals (no skarn). They are in heavily fractured and brittle rock with high permeability open to the surface and have been strongly affected by the collapse of the limestone above oxidized sulfide deposits. These deposit-associated caves were only discovered through mining activities and were not open to the surface with human enterable passages. These mineral deposits are not analogous to the Rosemont deposit, which is noted for its calc-silicate skarn that accompanies copper, molybdenum, and silver mineralization.

The elements in common for the Glove, San Xavier, and Bisbee mine caves are: extensive faults and open space fractures, replacement limestone (unmetasomatized, not skarn), and sulfide ore bodies that have undergone extensive oxidation that generated abundant copper carbonate and copper sulfate minerals, such as malachite, azurite, and brochantite. These are the result of subsidence oxidation, hydrothermal dissolution, or hypogenic dissolution cave-forming processes, as defined above (Section 2.1).

In contrast, the carbonate host rocks at Rosemont have been extensively transformed into dense and less soluble skarn minerals (garnet and other calc-silicates), and there is relatively little oxide ore compared to the volumes of sulfide ore. The surface outcrops show mineralized, intensely fractured and highly oxidized rock that would not support a cave structure (Figure 13). The evidence to date suggesting the lack of cave resources in the immediate project area does not negate the possible occurrence of a cave or other solutional feature being discovered during construction, excavation, or blasthole drilling activities. Decreasing the probability that a pre-mineralization cave could survive intact or that a post-mineralization cave could form includes the:

(1) intense surface fracturing that has weakened the potential cave-supporting beds, (2) metasomatism and generation of skarn minerals obliterating the original limestone composition and textures, (3) deep burial by Cretaceous and Tertiary sedimentary formations, (4) lack of thick oxidation zone relative to oxidation zones found elsewhere, and (4) the tightness (lack of pore space) in the skarn formations as documented through aquifer testing.

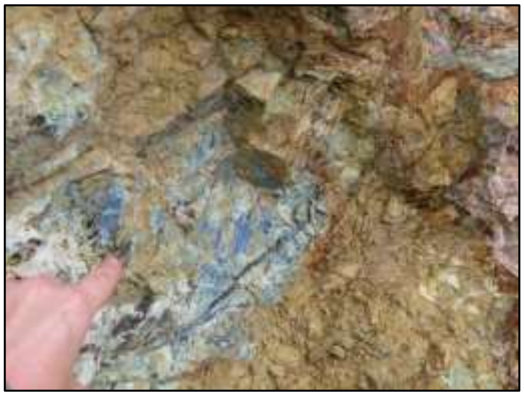


Figure 13 Oxidized Epitaph Formation showing malachite, chrysocolla, azurite, and iron oxide mineralization in intensely fractured outcrops (hand and hammer for scale) (SRK, 2012)

4 Summary and Conclusions

Dissolution features have been identified in carbonate formations of the northern Santa Rita Mountains and adjacent mountains. The dissolution features range from small holes, gashes, fissures, short-distance openings, and “shelter caves” to humanly enterable cave formations and underground mazes that venture into complete darkness. The cave resources are relict features that are wet, dry, or both on a seasonal basis, are located above the local water table, and are not connected to local or regional groundwater sources. The drip water and pools in the caves form in response to meteoric water – principally winter precipitation. The caves were formed by non-karst cave processes. Several caves are noted for the complexity of their cave passages and the abundance of their speleothems, and one cave is associated with metallic mineralization.

The four significant caves discussed in this article are located 7 to 16 miles from the center of the proposed Rosemont open pit. None are within the area of influence of the 5-ft and 10-ft groundwater drawdown contours projected to result from the proposed operation per the results of two independent groundwater flow model (M&A, 2009; Tetra Tech, 2010). The known caves are formed in Pennsylvanian and Permian limestone beds. In the authors’ opinion, the moisture and speleothem characteristics of known cave resources in the Santa Rita and adjacent Whetstone mountains are most likely to be impacted by changes in climate and local weather conditions, erosion, or human entry, rather than from impacts related to groundwater withdrawals associated with the proposed operation.

The lack of cave resources identified in carbonate formations at the project site is attributed to the transformational effects of magmatism, metasomatism, and mineralization that have significantly altered the original limestone host units to marble, hornfels, and skarn. The calcium carbonate combined with silica- and metal-bearing brines formed a new mineral assemblage consisting of calc-silicate skarn minerals. Many of these new minerals (such as quartz and garnet) are denser and more resistant to solution etching and dissolution than the original host formations.

None of the evidence discussed above completely negates the possibility of finding an open fissure or cave in the deposit area or other areas of planned surface disturbance (roads, tailings and waste rock storage areas). Based on the weight of evidence researched by these authors, however, the probability of finding a cave resource similar to the small caves in Sawmill Canyon or the four significant caves discussed in this article is low.

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