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Shelved as: GB 601.A2 A4 2009

Location:

Title: National Cave and Karst Symposium 1 ; Advances in Hypogene Karst Studies /

Volume:

Issue:

Date: 2009

Article/Paper: ; Hypogenic origin of robber baron cave; implications on the evolution and management of the edwards aquifer, central texas, usa

Pages: 85-98

OCLC #: 437009571
ISSN:

Lender string: UIU,*LHL,GIS,IXA

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HYPOGENIC ORIGIN OF ROBBER BARON CAVE: IMPLICATIONS ON THE EVOLUTION AND MANAGEMENT OF THE EDWARDS AQUIFER, CENTRAL TEXAS, USA

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Abstract
Robber Baron Cave is formed within the Upper Cretaceous Austin Chalk, in Bexar County, Texas, USA. The cave exhibits features that demonstrate a hypogenic origin, including a 1.51-km-long network maze pattern, fissure-floored passages, passage ceilings laterally enlarged adjacent to a contact with an upper confining unit, and authigenic sediments. The Edwards Aquifer provides the only source of water that could create the conditions necessary to form the cave, and provides modern analogs through artesian flows from the nearby San Antonio and San Pedro Park Springs. Anecdotal reports from the early 20th century describe flowing streams and pools in sections of the cave no longer accessible.

The Edwards Aquifer enlarged westward by stream incision along the Balcones Fault Zone, exposing down-faulted permeable units to allow groundwater discharge from lower elevation locations. Stream incision rates indicate that the hypogenic conditions necessary to form Robber Baron Cave occurred 2.0 to 2.5 Ma, and thus set a minimum age for accretion of the Bexar County portion of the aquifer. The presence of this and other hypogenic caves and artesian springs in the Austin Chalk, above the upper confining unit of the Edwards Aquifer, demonstrates areas of significant localized upward flow into the Austin and the paleo land surface. Identification of these areas is important in establishing areas of more stringent land use regulations to prevent aquifer degradation through these highly permeable features situated outside of the recognized aquifer recharge zone.

Introduction
Robber Baron Cave is located within the city of San Antonio, in central Texas, USA. It is by far the most extensive and best known cave in Bexar County. The earliest reports of the cave date to the 1910s. From 1926 -1933, about 160 m of its passages were developed for tourists. This included the placement of electric lights and the partial filling and leveling of the floors to create easy walkways. The developed areas were passages in the northern third of the cave.

Currently the cave has 1.51 km of known passages within a square area approximately 100 m on each side (Figure 1). It is a predominantly horizontal network maze of linear passages intersecting at 30-90° angles. The entrance is a sinkhole measuring 11 m long by 9 m wide by 3-9 m deep and formed by collapse at the intersection of least three passages. The sinkhole had

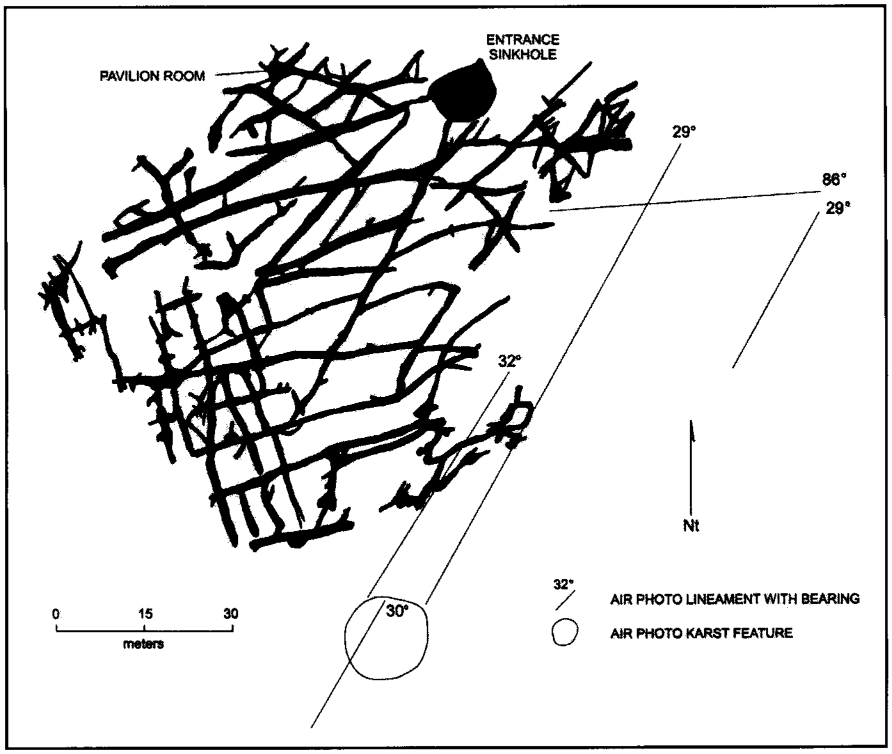

Figure 1. Silhouette map of Robber Baron Cave and aerial photo lineaments, updated from Veni (1988, 1997a) with surveys conducted in 2008.

been half filled with dumped dirt and debris since at least the 1950s until cleaned out from 2003-2004, when a trench was cut into the north side of the sinkhole for easier access (Mitchell and Palit, 2009). Two of the three passages in the sinkhole are open to the surface; one is blocked by bars and the other, at the deepest point of the sinkhole, is gated to protect the cave from vandalism and unauthorized visitation.

The majority of passages in Robber Baron Cave are about 1 m wide by 1-3 m high. Many walls are covered with a layer of flowstone usually <2 cm thick. Several walls taper to "V"-shaped cross sections or narrow rifts 1-3 m deep, so the floor areas in these passages are relatively small. Clay is common on the floors. Gray clay is either washed or carried in material and brown clay is composed predominantly of the insoluble residual from the Austin Chalk that dissolved to form the passages (demonstrated in the following sections). The clay usually ranges from about 3 cm to a meter thick, although a systematic sounding of clay depths has not been conducted. Excavation of a pit into the floor of the Lighted Passage in 1977 demonstrated the sediment was at least 3 m deep. However, most of this was artificial fill. Sediment depth decreases with distance from the sinkhole, and the cave's mean depth generally increases with that distance, probably a direct correlation to the thinner sediments. The northern third of the cave averages roughly 10 m below the surface, the west-central portion averages a depth of about 12 m, and passages in the southern third of the cave rise to a depth of 8-10 m. A sediment-filled pit along the west-central margin of the cave was excavated to reveal the "Lower Level," which has at least 75 m of passages averaging 17 m below the surface.

Most of the cave's reported extent is not accessible for exploration or study. During its commercial development, the owner at the time deliberately collapsed many passages. Road building, underground utility lines, and other construction associated with the area's urbanization invariably added to the collapse. Prior to the collapses, Robber Baron was known to extend at least 100 m farther east to a water well, 600 m southwest to a now-sealed, extensive, but poorly explored maze cave known as Holmgreen's Hole, and about 1.2 km to the southwest to underground streams, pools, and another well that pumped water from the cave. Two caves sealed by urbanization have also been reported within 500 m of Robber Baron, and could potentially have connected to the cave. Since the late 1970s, cave explorers have excavated the collapsed passages in hopes of rediscovering the "lost" parts of the cave. Much of that effort and the cave's history is recorded by Veni (1988) and updated by Veni (1989, 1997a).

Geologic setting

Robber Baron Cave is located at the southeastern corner of the karstic Edwards Plateau. Its entrance is at an elevation of 250 m above mean sea level at the northern edge of an effectively level upland area between Olmos and Salado creeks, situated 3 km to the southwest and east, respectively. Local surface drainage at the cave flows northeast to Salado Creek, while regional surface water flow is to the southeast.

The surface above Robber Baron Cave is about 4.5 m below the top of the Upper Cretaceous (Coniacian) Austin Chalk Group. Locally comprising the Atco, Vinson, and Dessau formations (Table 1), the Austin ranges in thickness in Bexar County from 40 to 73 m. Barnes (1983) described the Austin as "chalk and marl, chalk mostly microgranular calcite with minor foraminifera tests and *Inoceramus* prisms, averages about 85% calcium carbonate, ledge forming, grayish white; alternates with marl, bentonitic seams locally, recessive, medium gray, sparsely glauconitic, pyrite nodules in part weathered to limonite common, occasional beds with large-scale cross-stratification; locally highly fossiliferous." Its stratigraphy in the Bexar County area has not been well described but has been generally discussed by Holt (1956), Arnow (1959), Pessagno (1969), Cloud (1975), Waddell (1977), Dravis (1979), Corbett (1982), Barnes (1983), Young (1985), and Corbett et al. (1991). Detailed descriptions of the Austin have not been published, and its formation boundaries are not locally mapped, but the cave's gross

***Table 1**. Stratigraphic column of the Bexar County, Texas, area (wide lines represent unconformities).*

Age	Group	Formation	Average Thickness (m)
Upper Cretaceous/ Coniacian	Taylor	Pecan Gap Chalk	30-122
Upper Cretaceous/ Coniacian	Austin		40-73
		Dessau	inadequately mapped
		Vinson	inadequately mapped
		Atco	inadequately mapped
Lower Cretaceous/ Cenomian-Albian	Washita		32.5-37.5
		Buda Limestone	16.5
		Del Rio Clay	16.0
		Georgetown	0-5
Lower Cretaceous/ Albian	Edwards		147.1

stratigraphic position at the top of the group indicates it lies within the Dessau Formation.

Textural and mineralogical observations and analyses of the Austin Chalk

This study provides the first published microprobe imaging, chemical mapping, and quantitative analyses of the Austin Chalk from the Bexar County outcrop. Eight samples described below were collected from the cave. Two sediment samples from within the cave were also collected and are described later in this paper.

All samples were examined using a Cameca SX-100 microprobe located at the New Mexico Institute of Mining and Technology. Polished samples of all but the two sediment (clay) samples were prepared. Samples were examined using backscattered electron (BSE) imaging. Chemical maps showing the distribution of Ca, Si, and Fe were collected in representative areas of three rock samples (RBC 8 through RBC 10). Quantitative analyses were performed on all polished samples. An accelerating voltage of 15 kV and a 10 nA beam current were used. Analyses of carbonate or mixed matrix material were done using a broad (10 or 20 micron) beam. A point beam (~1 micron) was used for all other analyses. Standard reference materials, including amphiboles and carbonates were run in each analytical session to assess and monitor calibration accuracy and reproducibility.

Because their tight matrix and consequent low permeability inhibited infiltration of the epoxy, relatively flat unpolished surfaces of the clay samples were mounted on carbon tape and qualitative scans performed to determine their composition; a few quantitative analyses were performed on RBC 4 to determine any distinction between observed color variations in the clay.

Two distinct lithologic horizons occur in the Austin Chalk at Robber Baron Cave. Approximately the upper 13 m of the Austin, extending about 8 m below the surface at the cave, are a pale yellow (Munsell 2.5Y 8/2), soft, massive, highly fractured chalk. All solutionally-formed passages occur below the chalk within a hard, fossiliferous limestone horizon. The chalk is often exposed in the cave at the top of collapse-formed domes that stoped up from the underlying limestone. The chalk horizon has been referred to as a marl in some previous reports, which is consistent with chemical maps and BSE images of sample RBC 10, which show microscopic fossils and carbonate fragments with occasional glauconite grains in a finer matrix of dominantly broken shell fragments and glauconitic clay (Figure 2).

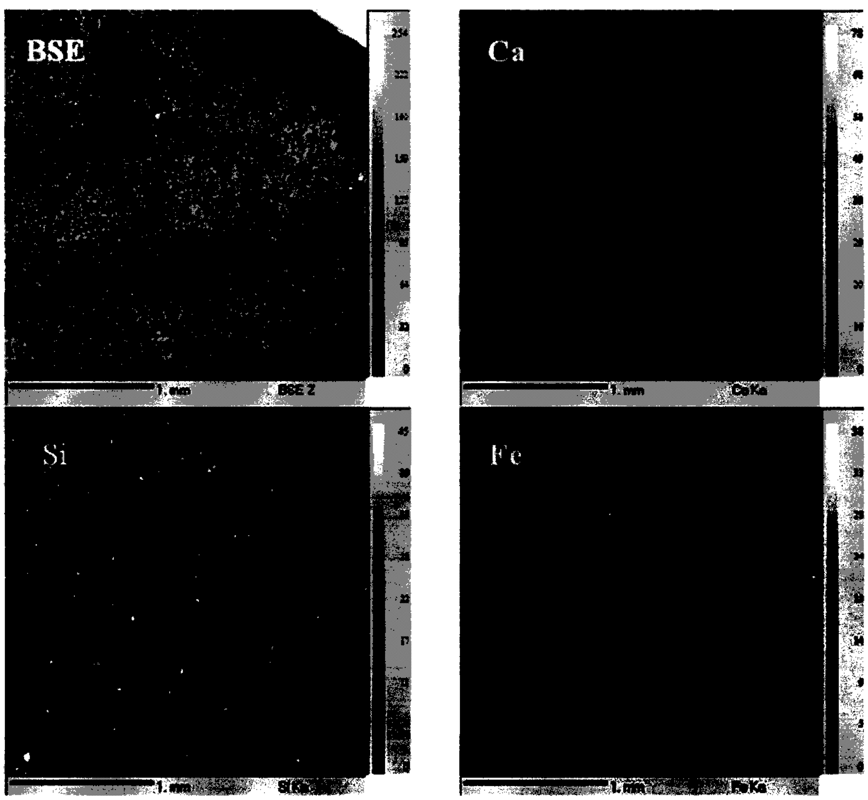

Figure 2. BSE image and Ca, Si, & Fe element maps of chalk horizon of Austin Chalk (sample RBC 10).

Goethite nodules (referred to in the literature by the generic term "limonite") occur in both the chalk and limestone horizons. RBC 2 is a nodule from the chalk horizon with a yellow (Munsell 10YR 7/6) rind. BSE images and quantitative analyses show a dense core of dominantly goethite with minor siliceous inclusions, rimmed by a porous 500 micron thick outer rind (Figure 3-A). The rind is dominantly composed of fine calcium carbonate fragments, grains, and cement intermixed with goethite crystals and cement. Glauconite pellets and quartz grains are incorporated in the rind in some areas and some carbonate fossils are replaced by goethite (Figure 3-B). RBC 3 appears typical of weathered goethite nodules in the cave walls. They have a weathered reddish brown color (Munsell 7.5YR 6/6), and RBC 3 was found to be made up stratigraphic position at the top of the group indicates it lies within the Dessau Formation.

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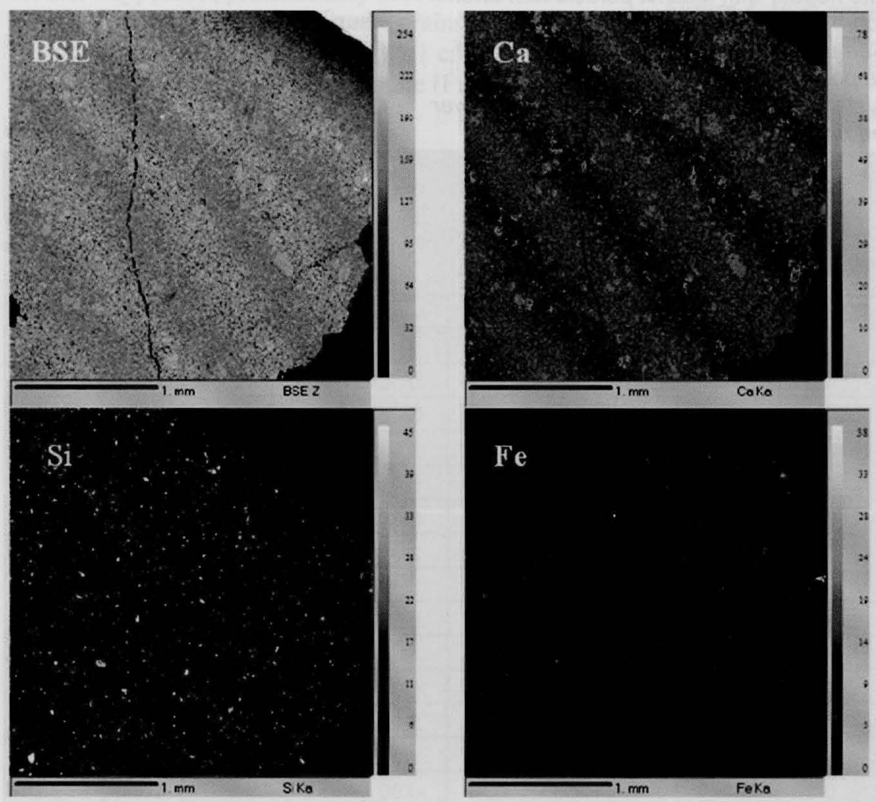

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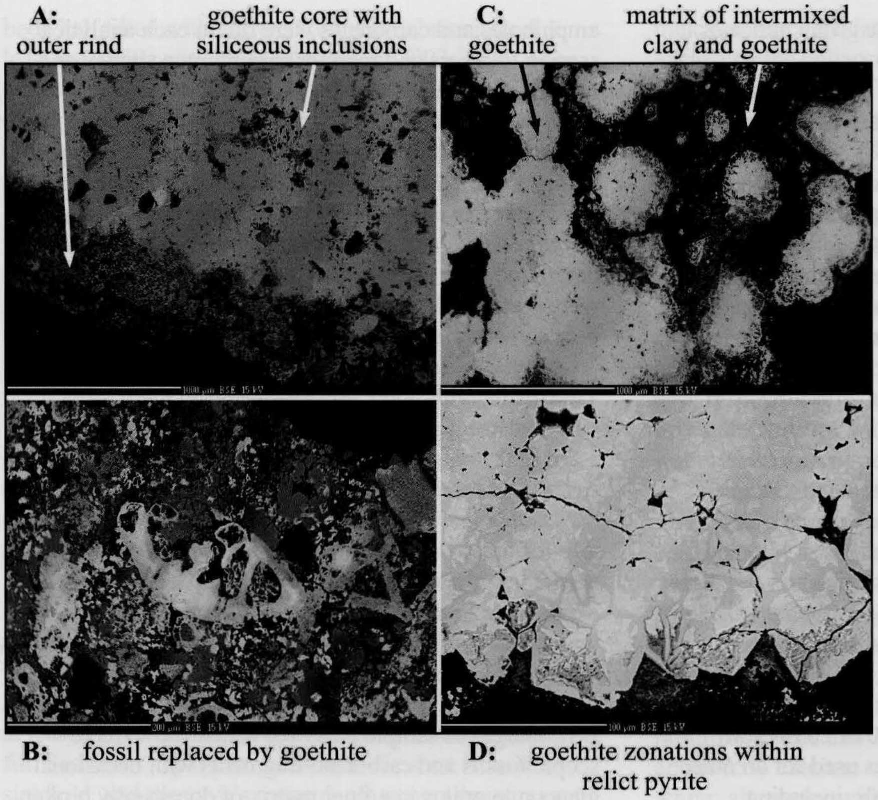


Figure 3. Sample RBC 2; A: Goethite nodule with distinct particle-rich rind. B: Close up of rind showing mix of carbonate (medium gray) and goethite (bright areas) grains and cement. Sample RBC 3; C: Aggregate clusters of zoned goethite crystals rimmed by a porous matrix of glauconitic clay and goethite. D: Close up of goethite crystals showing higher Z (bright) and lower Z (dark) zonations and highly altered rims of outer crystals.

of clusters of aggregate crystals (altered pyrite) with distinct zonations loosely rimmed by a porous matrix dominantly composed of glauconitic clay intermixed with fine iron-rich material (goethite) (Figure 3-C). Well-developed crystal faces along outer edges of clusters are significantly altered. Quantitative analyses within goethite zonations with a lower average atomic number or "Z" (appear darker in BSE images) have higher concentrations of Si and Al, and lower Fe content than higher Z zonations (Figure 3-D, Table 2).

The Austin Chalk's limestone horizon at Robber Baron Cave is at least 9 m thick. Its upper 2 m are a highly fossiliferous zone, increasing in fossil content downward to become a dense accumulation of *Exogyra* (?) *laeviuscula* gastropods. It rests unconformably on a burrowed surface extending about 50 cm into the underlying limestone (Figure 4), which generally weathers in the cave to a predominantly yellow (Munsell

Table 2. Quantitative analyses of light (higher average atomic number or Z) and dark (lower Z) zonations in goethite crystals (% weight oxide).

Goethite Analyses	P_2O_5	SiO_2	SO_2	TiO_2	Al_2O_3	MgO	CaO	MnO	FeO	Na_2O	K_2O	Total
RBC 3-01	0.26	4.80	0.05	0.00	1.04	0.20	0.31	0.01	68.04	0.01	0.01	74.72
RBC 3-03	0.26	4.81	0.05	0.06	1.10	0.25	0.36	0.00	67.34	0.02	0.00	74.24
RBC 3-05	0.27	4.95	0.01	0.02	0.98	0.21	0.46	0.01	67.71	0.02	0.02	74.64
RBC 3-18	0.24	4.91	0.04	0.01	1.14	0.24	0.31	0.03	66.59	0.01	0.00	73.50
RBC 3-19	0.45	6.11	0.04	0.13	2.57	0.21	0.60	0.01	65.08	0.01	0.02	75.22
RBC 3-26	0.33	5.98	0.03	0.00	1.53	0.26	0.41	0.00	66.28	0.03	0.01	74.86
RBC 3-27	0.33	6.64	0.04	0.03	1.45	0.22	0.48	0.01	67.53	0.00	0.00	76.73
RBC 3-34	0.18	5.12	0.02	0.00	1.09	0.23	0.31	0.02	67.46	0.00	0.00	74.42
Avg. low Z	**0.29**	**5.41**	**0.03**	**0.03**	**1.36**	**0.23**	**0.41**	**0.01**	**67.00**	**0.01**	**0.01**	**74.79**
RBC 3-02	0.26	3.11	0.06	0.04	0.53	0.18	0.34	0.00	72.15	0.00	0.01	76.69
RBC 3-04	0.34	3.20	0.06	0.03	0.71	0.18	0.45	0.04	73.59	0.00	0.03	78.61
RBC 3-17	0.39	3.43	0.04	0.02	0.69	0.13	0.51	0.00	72.85	0.00	0.00	78.06
RBC 3-25	0.36	3.52	0.02	0.03	0.73	0.08	0.45	0.00	74.06	0.02	0.01	79.28
RBC 3-35	0.27	3.25	0.07	0.02	0.55	0.14	0.39	0.00	71.98	0.00	0.01	76.66
Avg. hi Z	**0.32**	**3.30**	**0.05**	**0.03**	**0.64**	**0.14**	**0.43**	**0.01**	**72.93**	**0.00**	**0.01**	**77.86**

10YR 7/6) surface. While the burrowed interval has no apparent effect on cave development, most passages in the cave occur in its host and underlying limestone. This limestone is grainy and contains some fossils; abundant glauconite and quartz grains and occasional goethite grains appear in the BSE images of sample RBC 8 (Figure 5). The limestone in the cave's lower levels has not been sampled or carefully examined; frequent high percentages of atmospheric carbon dioxide preclude regular access to that part of the cave.

The limestone's fossiliferous zone has abundant glauconitic grains and pellets, as illustrated in BSE images of sample RBC 9 (Figure 5). The burrow fill material (sample RBC 5) is dominantly composed of clasts of poorly cemented, predominately finely crystalline calcium carbonate with some larger crystals and fossil remnants. Some clasts in the sample contain abundant glauconite pellets intermixed with carbonate; porous matrix material of intermixed glauconitic clay and carbonate surrounds some of the clasts (Figure 6). RBC-6, a sample of pale brown (Munsell 10YR 6/3) crust that lines some of the burrows, is composed of glauconite grains in a porous matrix of clay intermixed with carbonate cement. Goethite appears to preferentially coat and fill fractures within many of the glauconite grains (Figure 5). RBC 7, a gray (Munsell 10YR 5/1), <1 cm long siliceous crystalline boxwork structure (Figure 5) was

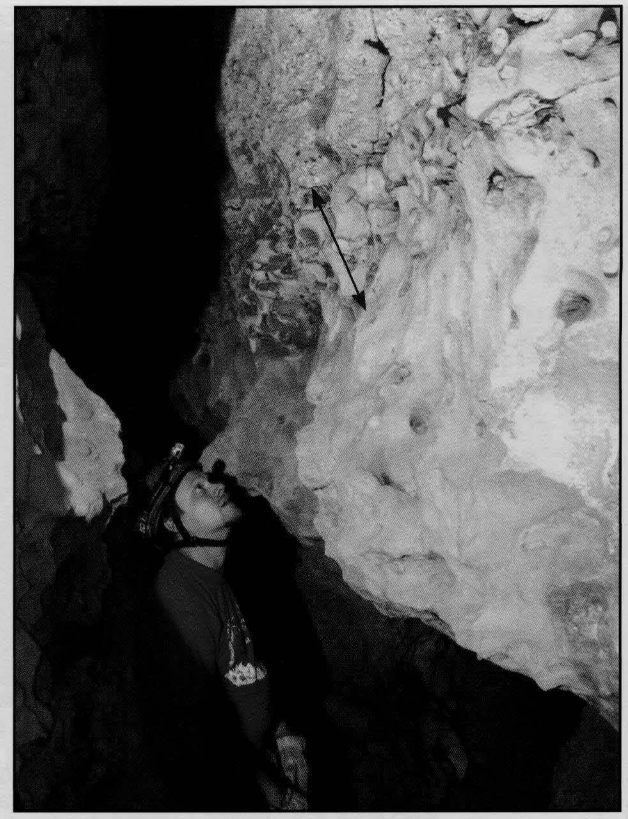
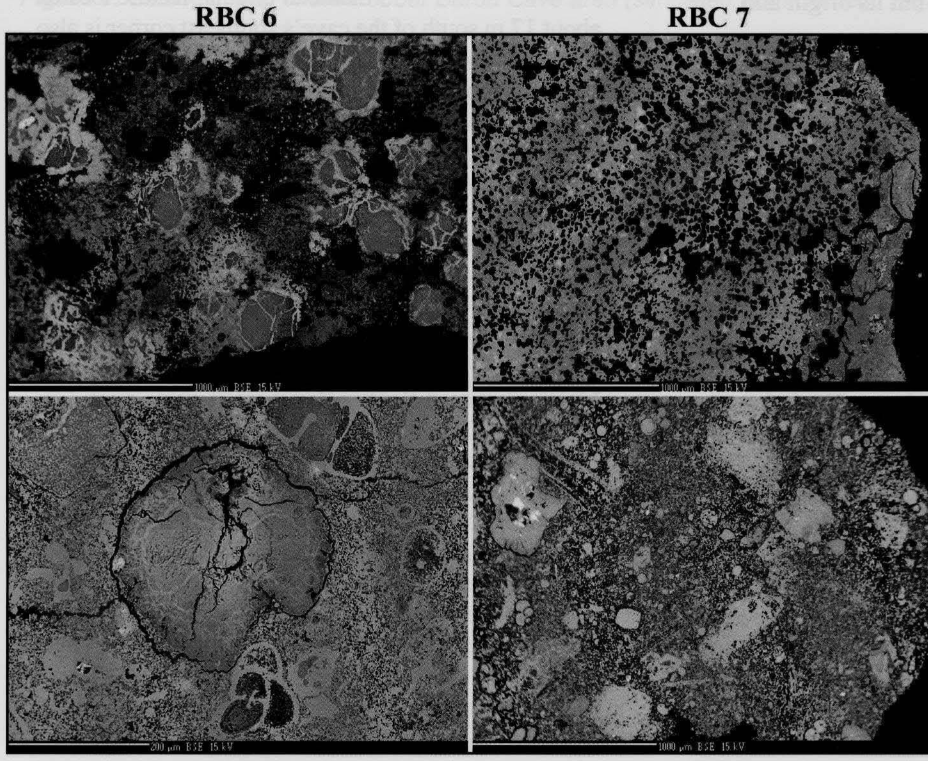


Figure 4. Blue arrow spans the width of filled burrows in the Austin Chalk, below the highly fossiliferous zone at the top of the limestone horizon.

RBC 6 RBC 7



RBC 8 RBC 9

Figure 5. BSE images; RBC 6) goethite coated glauconite grains in mixed carbonate and clay matrix; RBC 7) siliceous crystalline boxwork structure; RBC 8) close up of glauconite grain and carbonate tests in mixed carbonate-dominant and clay matrix; RBC 9) carbonate grains, tests and glauconite pellets in mixed carbonate-dominant and clay matrix.

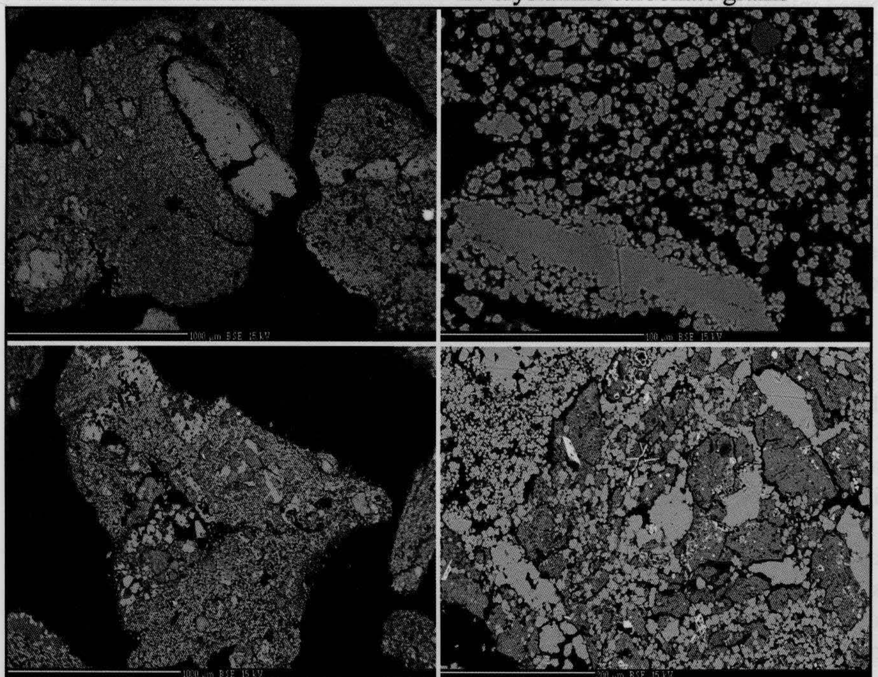


***Figure 6**. Sample RBC 5; A: Finely crystalline, dominantly carbonate clast with some larger carbonate grains or pellets. B: Close up of carbonate matrix showing loosely cemented, possibly recrystallized grains. C: Clast composed of abundant glauconitic pellets in carbonate cement. D: Close up of central portion of glauconite-rich clast. Bright specks are Fe-rich (goethite) grains.*

found associated with RBC 6, but its origin and significance are not known.

Geologic structure

Robber Baron Cave is in the Alamo Heights horst, an upthrown block of Austin Chalk that is the dominant structural feature of the study area (Figure 7) and which topographically stands 20-30 m above the surrounding terrain. The horst formed by tectonic stresses associated with its location within the Balcones Fault Zone, which developed along the homoclinal hinge between the relatively flat-lying strata of the Edwards Plateau to the northwest and the more steeply dipping strata in the Gulf of Mexico Basin to the southeast. The Balcones Fault Zone is characterized by a series of en echelon normal faults, mostly downthrown toward the gulf.

Five major faults define the Alamo Heights horst. About 700 m north of the cave, one fault strikes N60°E. Three faults extend southwest from the northern fault. Respectively 1.8 and 2.7 km west of the cave, two near-parallel faults strike N25°E and N30°E while the third fault is 2.4 km east of the cave strikes a mean N47°E. These three faults are truncated by a fault 4.2 km south of the cave which strikes N55°E. Cumulative average fault displacement is 75-110 m (Small, 1986). In the central section of the horst near the cave, Corbett et al. (1991) found that joints are generally vertical and trend N40° E. The beds within the horst are almost horizontal, but their exact attitude has not been precisely measured. No faults have been reported or mapped near the cave.

The geologic outcrop near Robber Baron Cave is almost entirely covered by urban development. No definitive fractures, sinkholes, outcrops, or other geologic features were found or are known within a 100 m radius. Cliffs and quarries in Olmos Creek and Salado Creek, which flank the Alamo Heights horst, provide the only opportunities (except within the cave) to closely examine the bedrock geology. No major geologic features were clearly apparent in aerial photographs, but weak lineaments that align with passages at the southwest corner of the cave almost certainly reflect joints in the bedrock. A 13-m-diameter circular feature located about 17 m south of the cave's southeast corner is also faintly visible on the air photos (Figure 1). While there is insufficient information to determine if it is natural or artificial, the feature's similar size to the entrance sinkhole, and three radiating lineaments that parallel major fracture trends in the cave, suggest it may be a collapse of the cave beyond the current limit of exploration. No evidence of the possible collapse structure or fractures could be seen at ground level, but the surface is highly disturbed by decades of human activities (Veni, 1997a).

Most passages in Robber Baron are strongly joint-controlled. The orientation of linear passage segments can be measured from the map to approximate the joints' effect on the cave's development. The following discussion summarizes the analyses by Veni (1997a). The most dominant fractures guiding passage development range in orientation from N60-74°E, reflecting the nearby fault to the north, and comprise 27.9% of the cave's passages. The next most dominant group ranges twice as broadly from N25-54°E to include 24.5% of the passages, and reflects the N40°E jointing observed by Corbett et al. (1991) and the trends of the three faults

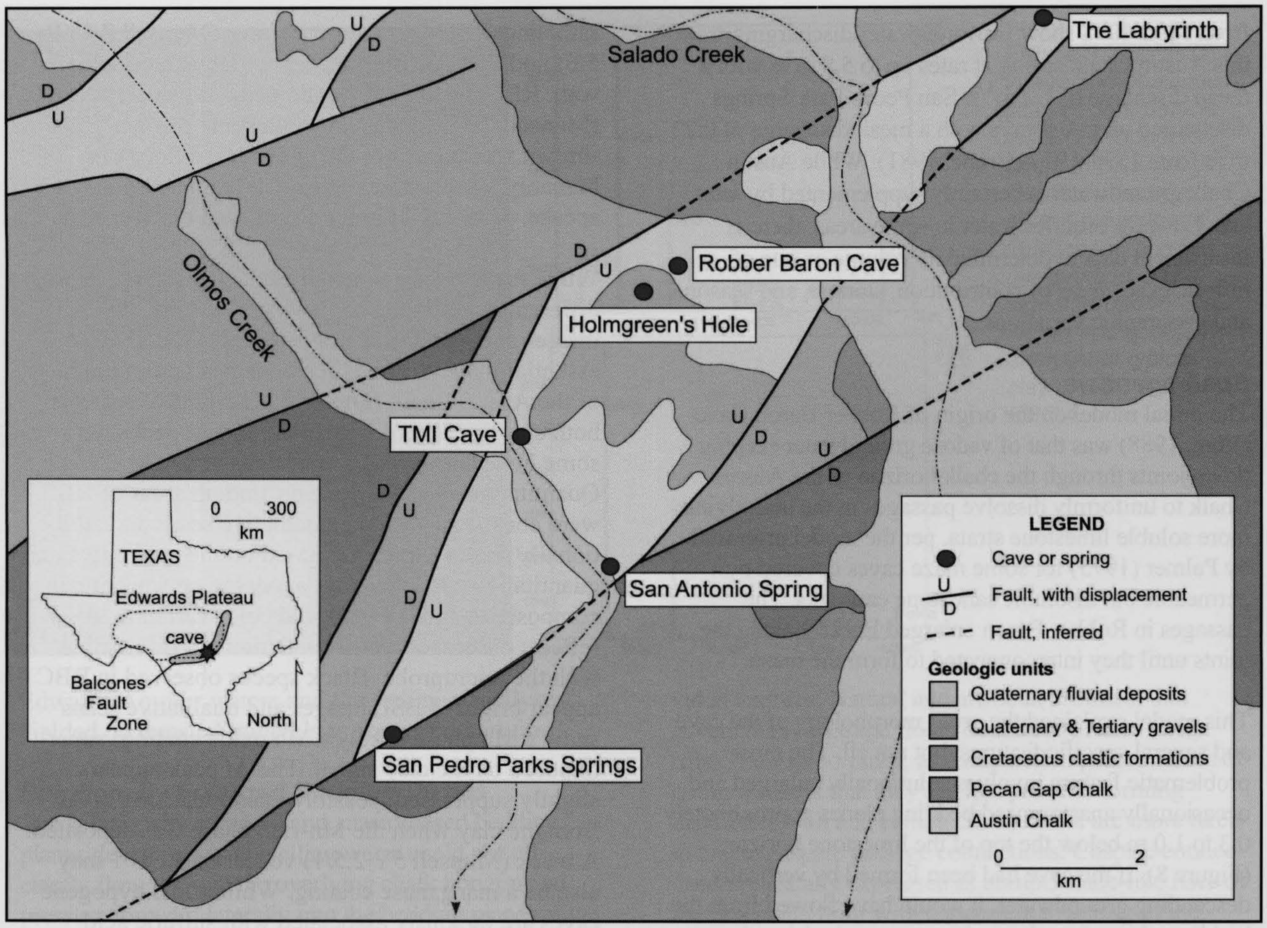


***Figure 7**. Geologic map of the Robber Baron Cave area (simplified from Barnes, 1983).*

east and west of the cave. While these segments are secondary in terms of total passage length, they include the longest segments in the cave, with the N60-74°E segments being slightly shorter. A third important group of passage segments include two ranges: N41-45°W and N16-25°W. These trends do not correlate to the known structural features of the horst and may be secondary products of the tectonic strain. These two groups differ significantly in their horizontal and vertical distribution. Segments oriented between N41-45°W occur in the northern part of the cave, and generally include the cave's highest elevation passages. In contrast, the N16-25°W segments are predominantly grouped at the west-central and southwestern side of the cave, comprise most of the deepest passages, and are smaller, generally having about half the cross sectional area. The depth differentiation in passage orientation may suggest elevations where certain fractures are more permeable; additional study is needed.

Austin Chalk hydrogeology

Little research has been done on groundwater in the Austin Chalk, and no potentiometric mapping has been conducted. Arnow (1959), George (1952), and Holt (1956) respectively described typical Austin groundwater in Bexar and neighboring Comal and Medina counties as yielding only small volumes to water wells, and as commonly high in hydrogen sulfide from the oxidation of the pyrite nodules within the chalk. However, Livingstone, Sayre, and White (1936) found that in some places in Bexar County, artesian water from the Edwards (Balcones Fault Zone) Aquifer (hereafter, "Edwards Aquifer") flowed upward along fractures to become Austin groundwater.

Data on groundwater flow between the Austin Chalk and the Edwards Aquifer are sparse (Veni, 1995). Contamination of the Edwards Aquifer from a landfill in the Austin Chalk reveals at least some downward interformational flow (Buszka, 1987). In contrast, significant volumes of rising artesian flow from the Edwards into the Austin is demonstrated at the San Antonio Spring in Olmos Creek, 4.5 km southwest of Robber Baron Cave, and San Pedro Park Springs 8 km southwest. Discharge records for San Antonio Spring from 1892-1978 show Edwards water discharging from this Austin Chalk spring at rates up to 5.8 m^3/s with a mean discharge of 1.2 m^3/s; San Pedro Park Springs discharged up to 0.8 m^3/s with a mean discharge of 0.22 m^3/s from 1895-1977 (Brune, 1981). While Austin Chalk groundwater is certainly supplemented by artesian Edwards Aquifer water in some areas, there is insufficient data to determine its volume or rate of inflow, exact areas of contribution, storage, and seasonal and geographic variations.

Speleogenesis

The initial model on the origin of Robber Baron Cave (Veni, 1988) was that of vadose groundwater seeping down joints through the chalk horizon of the Austin Chalk to uniformly dissolve passages in the underlying more soluble limestone strata, per the model proposed by Palmer (1975) for some maze caves covered by permeable but insoluble sandstone caprocks. The passages in Robber Baron enlarged linearly along the joints until they interconnected to form the maze.

This model explained the gross morphology of the cave and several specific features, but not all. The most problematic feature involves solutionally enlarged and occasionally anastomosed bedding planes approximately 0.3 to 1.0 m below the top of the limestone horizon (Figure 8). If the cave had been formed by vertically descending groundwater, it would have flowed from the bedding planes into the main passages, incising the passage walls. Instead, little or no incision occurs and often the passage walls undercut the bedding planes. However, when Klimchouk (2007) proposed a hypogenic origin for the cave, by reversing the initially hypothesized downward direction of vertical flow through the cave, all of its features were easily explained. Klimchouk briefly identified side feeders and point features in the cave's floor as evidence of hypogenic flow. Three additional features discussed below in greater detail further support hypogene development: sediments, solutionally enlarged bedding planes, rifts in the floors, and cuspate passage connections.

Sediments

Two sediment samples were collected from the Pavilion Room at the north-central end of Robber Baron Cave; sediments observed in other parts of the cave had no discernible differences in appearance or setting to warrant sampling. RBC 1 is a strong brown (Munsell 7.5YR 5/6) nodular clay from a pocket high in a passage wall. RBC 4 is a finely laminated reddish brown (Munsell 2.5YR 5/4) clay, with some distinctly yellow -brown sections, from the undisturbed floor of a humanly inaccessible passage. It contains some white specks, probably calcite crystals, and black specks.

While the hand specimen of each clay sample appears different in color and somewhat in texture, BSE images and qualitative scans revealed that they are essentially identical and residual dissolution products of the Austin Chalk (Figure 9). Qualitative scans for both clays showed dominant Si and Al peaks with some Fe and minor concentrations of Ca, Mg, and K. Quantitative analyses done on smooth areas of RBC 4 were consistent with the qualitative scans and additionally showed trace Ti. Based on the qualitative and quantitative data, the clays appear to be smectitic in composition and the observed color variation likely reflects differences in Fe oxidation not discernible with the microprobe. Black specks observed in RBC 4 appear bright in BSE images and qualitative scans show a Mn phase (likely a Mn oxide coating) superimposed on the clay signal. The Al peak appears slightly suppressed, possibly due to leaching of Al from the clay when the Mn-rich phase was deposited. A black (Munsell 5Y 2.5/1) veneer on RBC 1 may also be a manganese coating. While some hypogene caves are famously associated with sulfuric acid dissolution and the deposition of exotic minerals, carbonic acid dissolution is expected from artesian

Figure 8. Solutionally enlarged bedding plane and anastomoses in the Graffiti Room of Robber Baron Cave. Yellow line marks the contact between the chalk horizon and the underlying limestone horizon (the dip of the line is due to the photograph's wide angle, not a dip in the strata).

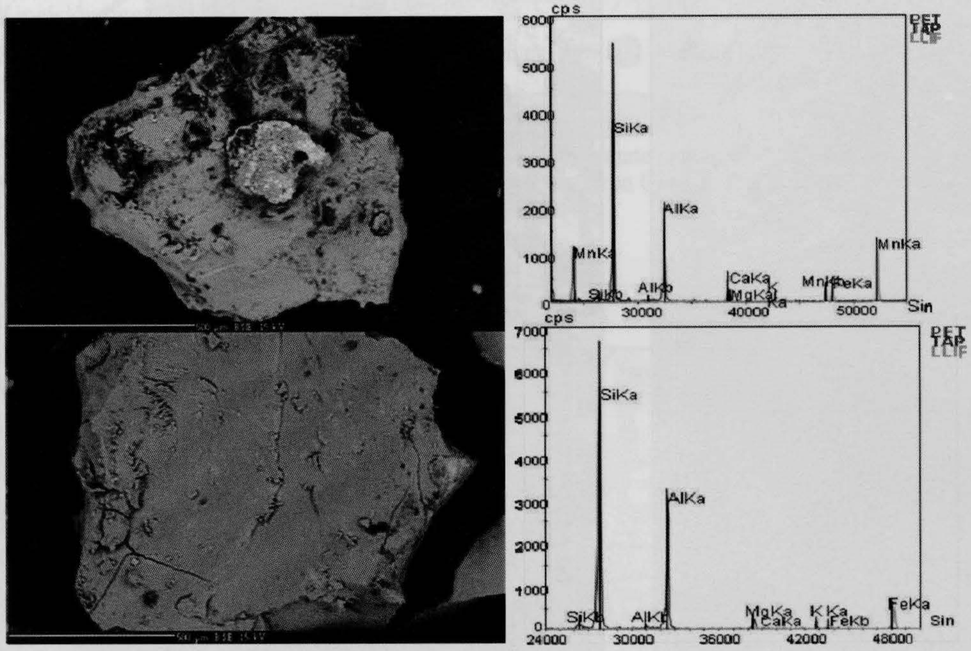


***Figure 9**. (top) BSE image and qualitative scan of dark particle in RBC 4 (appears bright in BSE image). Qualitative analysis shows presence of Mn-bearing phase overprinting clay signal; (bottom) BSE image and qualitative analysis of typical clay in RBC 1 and RBC 4.*

Edwards Aquifer waters and the sediment analyses yielded no unusual minerals to suggest otherwise.

Solutionally Enlarged Bedding Planes

The solutionally enlarged and anastomosed bedding planes developed as upwelling water could not efficiently flow through the overlying chalk horizon and pressure forced it laterally into the bedding planes at the top of the limestone. Enlarged bedding planes that decrease in size with distance from the main passage, until they eventually pinch, represent areas of groundwater storage, while those that connect to other passages represent a pressure gradient along which water flowed to discharge upward through fractures in the chalk. A precise leveling survey of these enlarged bedding planes (some are humanly passable) may identify the past hydrologic gradients, but their general prevalence near the northeast and southeast ends of the cave suggests the sinkhole and the circular aerial lineament may have been foci of groundwater flow through the chalk horizon into overlying strata now removed by erosion. Direct evidence of this flow through the chalk has not been found and is not expected. The chalk is slightly ductile, and where collapsed it often seals open fractures and gaps, so any hypogenically enlarged fractures or conduits in the chalk probably closed long ago.

Rifts and Cusps

Rifts in the cave floor (Figure 10) were described by Klimchouk (2007) as "point" sources of rising water, but are actually elongated along joints. Most range from 3-5 m in length, and the longest is at least 30 m. Some rifts are separated by narrow fins of limestone but hydrologically and morphologically function as undivided features. Natural and artificial sediment that covers many passage floors doubtlessly hides many rifts. Their importance, as compared to point sources of rising water, is that they are less prone to forming distinctive wall and ceiling channels but are more likely to create cuspate passage connections. Cuspate connections are usually expressed as abrupt, blade-like rises of the limestone floor with concurrent lowering of the ceiling along the axis of a passage to form relatively small windows within the passage (Figure 11). They can also occur between near-parallel passages. These windows are the most diagnostic feature of vertical groundwater movement; they would not exist in a regime with notable horizontal flow. Initially, individual passage segments developed along a joint above each rift. As upward flow was slowed by the overlying chalk, the segments enlarged laterally along the joints until they connected to form a cuspate window (Figure 12). In many locations, continued passage growth completely removed the windows.

Not all of Robber Baron's passages formed by rifts. Passages along the west-central and southwest side of the cave exhibit more classical elliptical phreatic morphologies and probably transmitted groundwater along less steep gradients, although more detailed surveys and studies are required to be certain of their origin. Ultimately, the Edwards Aquifer is the only viable source for the water, and the modern presence of Edwards water flowing from Austin Chalk wells and springs suggests that the cave developed when Edwards groundwater levels were significantly higher in the past.

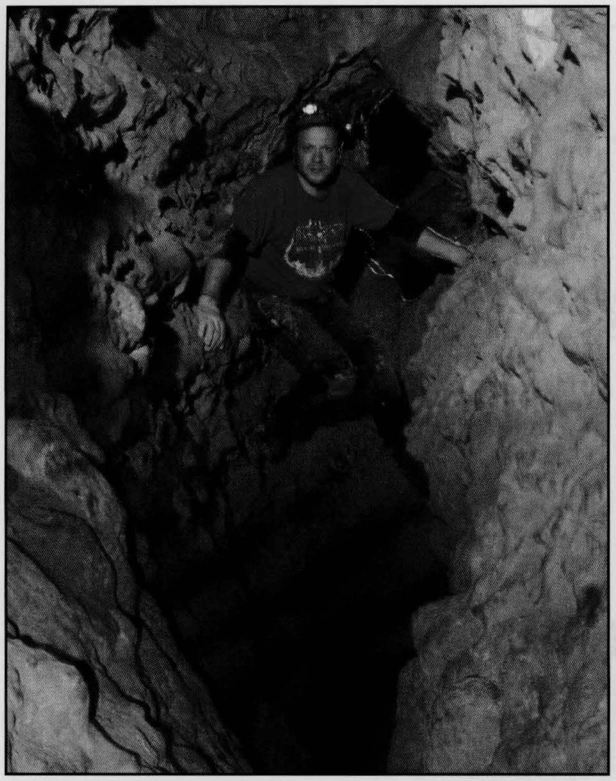


Figure 10. Example of a 5-m-long floor rift.

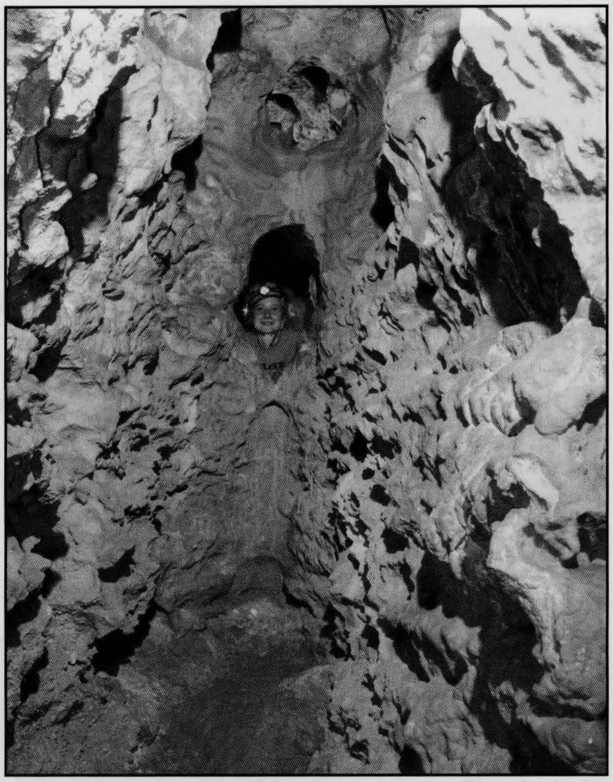


Figure 11. Cuspate window along the axis of passage.

Edwards Aquifer: evolutionary and management considerations

Groundwater flow in the Edwards Aquifer has developed in response to stream incision of the Balcones Escarpment, creating locations where springs can discharge Edwards water (Woodruff and Abbott, 1979). Preliminary assessment of cave distribution, morphology, origin, and regional hydrogeology suggests the aquifer grew west-to-east-to-northeast, as the groundwater drainage basins for ever-lower springs expanded headward until they captured water from older, higher elevation areas to progressively integrate the aquifer (Veni, 2009). The timing of these accretionary events has not been established, but the study of Robber Baron Cave provides some boundaries on the initial origin of San Antonio Spring and associated hydrologic changes within the aquifer.

The down-cutting of Olmos Creek can be used to constrain the time of the cave's origin. We considered the creek's elevation as an approximation for the elevation of the modern and past water table of the Edwards Aquifer in that area. Using the elevation of San Antonio Spring to reflect the mean modern water table, we found that Olmos Creek was 47.7 m higher in elevation to create hypogene conditions in Robber Baron Cave. This elevation is the current land surface at the cave and was used to approximate minimum artesian conditions. We slightly modified the mean

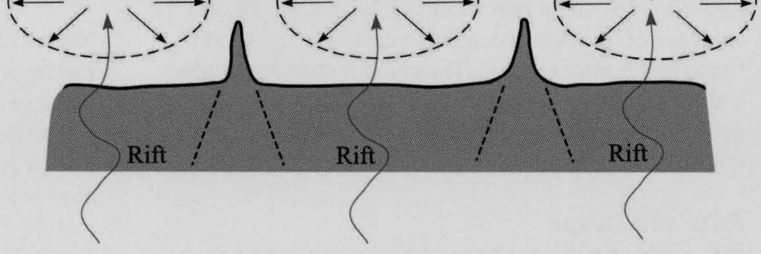


Figure 12. Schematic diagram of water rising from rifts in passage floors to create individual passage segments (ovals of dashed lines with arrows showing direction of growth) which linearly connect along joints to form cuspate windows; groundwater continues to ascend by leakage through the chalk.

incision rates for a nearby section of the Balcones Escarpment region (Veni, 1997b) to 19-24 mm/ka to better fit the conditions in Olmos Creek, and determined that Robber Baron Cave would have developed about 2.0-2.5 million years ago. This is significantly older than previously calculated by assuming an epigenic origin for the cave (Veni, 1994).

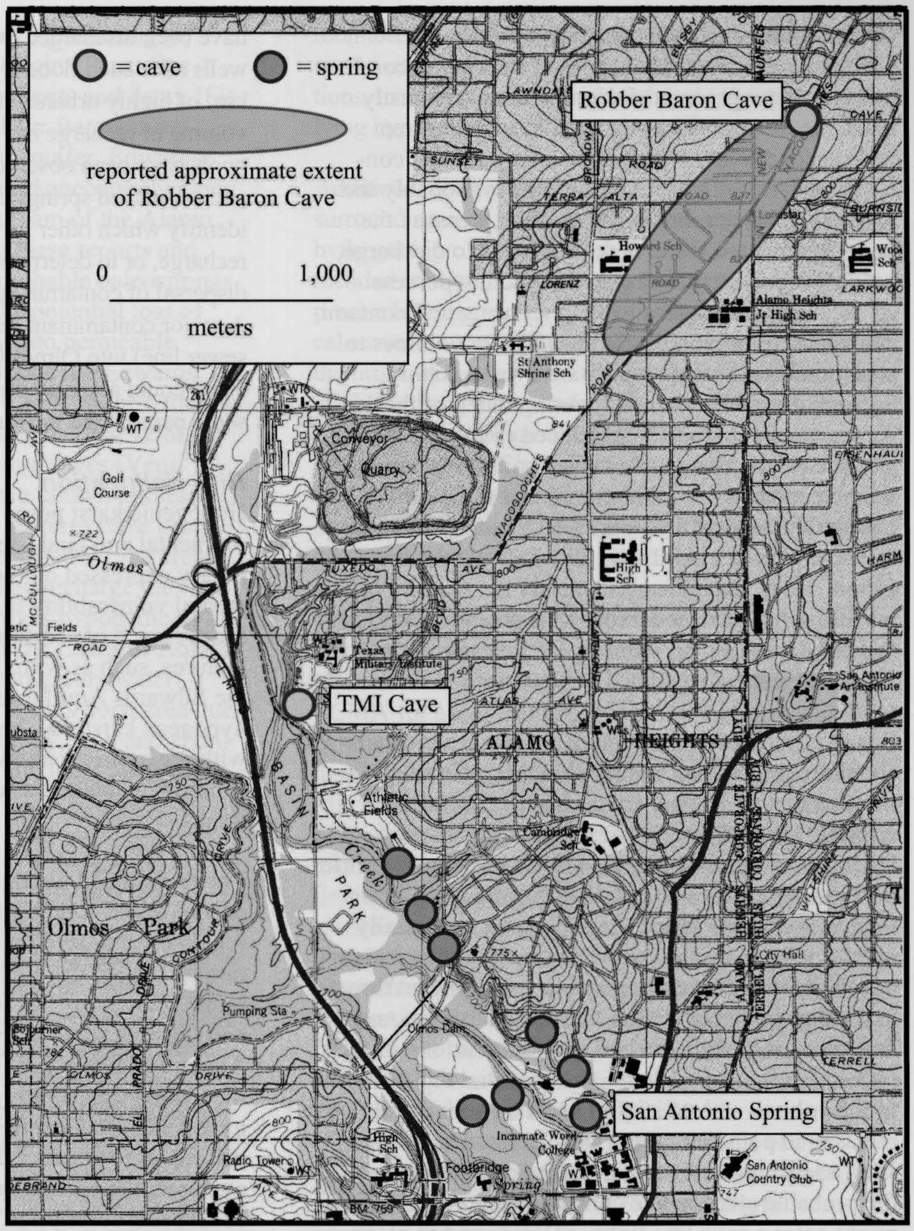


Figure 13. Topographic map showing the location of Robber Baron Cave and its estimated extent relative to TMI Cave and San Antonio and associated springs in Olmos Creek.

Robber Baron Cave aligns with other caves and springs in the area in a pattern suggestive of changing base levels for the aquifer (Figure 13). The cave reportedly deepens and connects with other caves and a well roughly 1.2 km to the southwest. Another kilometer southwest is a former quarry where more caves have been reported, some rumored to connect to Robber Baron. Another 1.2 km further southwest is TMI Cave. This 58 m long multi-entrance maze is in a cliff overlooking Olmos Creek and was initially considered a product of backflooding by the creek (Veni, 1988). While TMI Cave has been vadosely modified by floodwaters, further study of the area now strongly suggests it is a fragment of a once more extensive hypogenic cave. It is located at the junction of Robber Baron's southwest trend with the southeast trend of a series of springs that extend 2.3 km southeast to San Antonio Spring.

About 2 to 2.5 million years ago, Robber Baron Cave transmitted flow to the first or one of the first ancestral San Antonio Springs. There is no direct evidence to demonstrate that Olmos or Salado Creek extended over the cave in the past, except that as a hypogenic cave, Robber Baron most likely discharged into a significant topographic low which would probably be an ancestral Olmos or Salado Creek; Salado Creek is suggested by gravel deposits in a paleo-channel 1.1 km northeast of the cave. As both streams deepened and shifted to their present positions, the potentiometric surface for the Edwards Aquifer lowered, and cave development, and presumed overlying springs, extended southwest toward TMI Cave and Olmos Creek. Spring development then predominantly followed the northeast side of the creek as progressively younger springs arose to the southeast, with flow through the older springs becoming more intermittent with continued potentiometric declines. This evolutionary scenario poses the management considerations discussed below.

Groundwater contamination

Cavernous permeability from past hypogenic conditions creates a potential for contaminants to easily reach the modern Edwards Aquifer under current vadose conditions. The absence of significant contamination of the aquifer in this area is probably the function of three related factors. First, because the caves and related features were created to discharge, not recharge water, they generally do not possess surface catchment areas to channel water and contaminants into the Austin Chalk in sufficient volumes to pose imminent threats to Edwards water quality. Second, the chalk horizon covering much of the Austin results in a poorly developed epikarst. Additionally, the poorly permeable clayey soils of the area promote moderate to rapid runoff, and some form a caliche-like layer at their base which further inhibits recharge (Taylor et al. 1966). Third, due to the first two factors, most contaminants that enter the Austin Chalk are diffusely distributed through the area and with little hydraulic head, slowly entering the Edwards Aquifer at a rate where they are diluted below detection limits.

Despite the factors that protect against groundwater contamination in the Austin Chalk, significant pollution risks exist. Robber Baron Cave is home to six endemic invertebrate species, two of which are federally listed as endangered (U.S. Fish and Wildlife Service, 2000). Nothing is directly known about the tolerance of these species to pollutants; potentially even small and diffuse amounts of contaminants may adversely impact their populations. Significant threats to the aquifer occur at sites that store large amounts of hazardous materials, such as gasoline stations. If they occur over hypogenic karst, the potential danger is due to the volume and toxicity of pollutants that could be released in point locations. Detailed studies of the karst and hypogenic conditions are crucial to establish the probable areas where contaminants on the surface might enter a cave like Robber Baron, and to place hazardous materials where less karstification has developed for better containment in case of an accidental release.

The most significant risk of Edwards Aquifer contamination through the Austin Chalk occurs along Olmos Creek between TMI Cave and the San Antonio Spring. This is an area of enhanced permeability due to past and modern spring flows. Due to pumping of the aquifer, all of the springs periodically cease flowing and become estavelles, episodic sites of both recharge and discharge depending on potentiometric levels. When the springs aren't flowing, flooding of Olmos Creek recharges the Edwards Aquifer through these springs and paleosprings in the Austin Chalk. Turbid water and organic debris have been discharged from nearby artesian Edwards wells after such floods (Veni, 1985), which drain 88.2 km^2 of highly urbanized northern San Antonio. The volume of recharge has not been quantified, but whirlpools have been observed for days over the San Antonio and associated springs. No study has been conducted to identify which other Edwards wells intercept this recharge, or to determine the time of travel, dilution, and dispersal of contaminants before they reach those wells. A major contaminant release (e.g., tanker spill, ruptured sewer line) into Olmos Creek during such a recharge event could severely impair the drinking water quality in some parts of the Edwards Aquifer.

Risk delineation

Hypogenic karst poses a certain higher risk of environmental and land use problems because it is often poorly expressed on the land surface. Since environmental vulnerability in karst is frequently measured by the presence of solutional sinkholes and related features, such as with the state's regulations governing the Edwards Aquifer region, the vulnerability of hypogene karst may be significantly underestimated with regard to groundwater contamination, ground stability, endangered subsurface fauna, and related issues.

The presence of hypogenic caves is a clear indication of hypogenic conditions, but evolutionary studies of regional karst development is necessary for construction of conceptual models to define their probable range. This study has focused on Robber Baron Cave and illustrates that at least the southwest portion of the Alamo Heights horst, including adjacent sections of the Olmos Creek valley, have or still experience hypogenic groundwater flow. It is beyond the scope of this report to conduct digital modeling of groundwater movement to try and better define the area, but the conceptual description in this paper provides the framework for such modeling and especially for the development of a focused research program to more accurately delineate the area and its conditions.

At least two and possibly four other Austin Chalk areas in Bexar County are hypogenic and require further study: San Pedro Park Springs, The Labyrinth, probably Salado Creek, and possibly Culebra Anticline. The San Pedro Park Springs were previously mentioned in this report as discharging artesian water from the Edwards Aquifer. Several caves are reported nearby, but none are accessible, mapped, or studied; the area has been urbanized for about 100 years, and all reported caves are filled. The Labyrinth is an incompletely explored maze cave with at least 248 m of surveyed passage and morphologic features reportedly similar to Robber Baron Cave that strongly suggest it also has a hypogenic origin (Texas Speleological Survey, unpublished reports and data). It is located 6.4 km northwest of Robber Baron and is probably related to the Edwards Aquifer. Edwards Aquifer springs have been reported anecdotally along Salado Creek within and downstream of the Alamo Heights horst. A study verifying these reports and determining the distribution of probable paleosprings is warranted to better evaluate the potential loss of contaminated urban stream flow into permeable hypogene features that may recharge the Edwards Aquifer. The outcrop of Austin Chalk on the Culebra Anticline in western Bexar County holds several extensive and hydrologically active caves (Veni, 1997a). Phreatic morphologies are known in these caves, but no clearly hypogenic features have been noted. No springs have been identified for the area, and there is speculation that it may recharge the Edwards Aquifer. If this area proves hypogenic or a non-hypogenic recharge area for the Edwards Aquifer, it is potentially more vulnerable to groundwater contamination than the Alamo Heights horst area due to significant differences in lithology, soil, and abundant, focused, surface drainage into karst features.

Conclusions

The longest cave in Bexar County, Robber Baron Cave is also without a doubt the most complicated. This maze cave has a long history of exploration, yet most of its passages are currently inaccessible. It formed hypogenically from artesian water in the Edwards Aquifer that rose to the surface 2 to 2.5 million years ago, to flow as possibly the first location of the ancestral San Antonio Spring. The alignment of the cave with other caves, springs, major fracture patterns, and the likely direction of the lowering potentiometric surface with the incising Olmos Creek, strongly suggest a physical and hydrological connection as the cave's conduit network and its overlying spring system migrated 3.4 km southwest to TMI Cave and then 2.3 km southeast to the current site of the San Antonio Spring.

Understanding the cave's origin and how the evolution of the Edwards Aquifer and San Antonio Spring are related allow better delineation and study of previously unrecognized areas that pose potential risks to aquifer quality. Understanding of hypogenic processes and identification of key features and conditions also make it possible to study other areas in the region to determine if currently unrecognized hypogenic connections exist with the Edwards Aquifer that warrant investigation and protection. Existing hazardous material storage facilities over the known, reported, and projected extent of Robber Baron Cave should be at be more carefully monitored for leaks or spills; proposed facilities should not be sited without detailed hydrogeologic investigations, including geophysical surveys for possible underlying hypogenic conduits.

Additional research in Robber Baron Cave and the surrounding area would better define and delineate its hydrogeologic history and physical limits. Recommended studies include detailed stratigraphic mapping, a precise leveling survey of key passage levels, geophysical surveys to determine the density of passages beyond the limits of modern exploration, speleothem dating to establish the upper boundary on the timing of vadose conditions, hydrologic investigation of groundwater within the Austin Chalk, including tracer studies when San Antonio Spring and other estavelles in Olmos Creek are recharging, and most especially, further exploration of the cave and other caves in the area.

Acknowledgments

Robber Baron Cave is owned by the Texas Cave Management Association (TCMA). Our thanks go to TCMA for access and permission to collect samples from the cave for analysis, especially TCMA President Linda Palit, Robber Baron Cave Manager Joe Mitchell, and TCMA members Dr. Evelynn Mitchell of St. Mary's University, Courtney and Rick Corbell, and Michael Cunningham who assisted with the fieldwork. Countless others have given valuable assistance, advice, insights, and provided sounding-boards for ideas in over 33 years of exploration and research at the cave. Karen Veni carefully proofread the manuscript. The Cameca SX-100 electron microprobe at the New Mexico Institute of Mining and Technology was partially funded by National Science Foundation Grant STI-9413900. We also acknowledge the kind assistance of Nelia Dunbar, of the New Mexico Bureau of Geology and Mineral Resources, and an anonymous reviewer for their helpful comments on the manuscript.

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