Investigations of the Possible Underground Extent of La Posta Quemada Sinkhole: Colossal Cave Mountain Park, Pima County, Arizona

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Introduction and location of study area

The purpose of this investigation is to assess the possible underground extent of a sinkhole in Colossal Cave Mountain Park southeast of Tucson near Vail, Arizona (Figure 1). The sinkhole is located in a low terrace adjacent to La Posta Quemada (LPQ) Wash. In this report the sinkhole is referred to as LPQ sink. LPQ sink has grown in volume and extent since its initial appearance in the fall of 1994 and has undermined a park road used to access La Selviglia campground and picnic area. Park visitors must now detour around the sinkhole into LPQ Wash in order to access the campground. Colossal Cave Mountain Park is a Pima County park currently operated by Ortega National Parks LLC. Fencing and signage prohibiting entrance was installed around LPQ sink to prevent injury to park visitors unaware of the unstable nature of the sinkhole and surrounding area. Unfortunately, LPQ sink has continued to grow in size over the past several years and now extends beyond the fenced area. The Pima County department of Finance and Risk Management contracted with the Arizona Geological Survey (AZGS) in the fall of 2017 to assess the extent of underground voids associated with LPQ sink in order to predict the limits of possible surface collapse. To best delineate the extent of underground voids AZGS employed a combination of surface mapping, detailed surface topography surveys, and geophysical surveys including microgravity and electrical resistivity void mapping. This report summarizes the findings.

Figure 1. Location of study area.
Description of LPQ sink and geologic setting

A sinkhole is a depression or hole in the ground caused by collapse of near-surface material into an underlying void. Naturally occurring sinkholes are typically associated with dissolution of underlying carbonate or evaporate rocks. The hillslopes on both sides of LPQ Wash are composed of highly fractured and faulted carbonate rocks including Concha, Horquilla, and Escabrosa limestone (Richard et al., 2001). Colossal Cave, a tourist cave and namesake of the park, is located within Escabrosa limestone approximately 500 m (1,600 ft) to the west-northwest. The cave system consists of “an irregular maze” of caverns totaling approximately 3 km (2 miles) formed by dissolution of carbonate rocks along faults, joints and fractures (Brod, 1987). The extent of the known Colossal Cave system extends primarily north from the entrance and no connection to the area of LPQ sink is known. Other large cave systems, such as Kartchner Caverns in the Whetstone Mountains near Benson, Arizona, also occur within the Escabrosa limestone.

LPQ sink is a steep-sided, roughly circular to oblong depression approximately 7 m (23 ft) by 4.5 m (15 ft) across and 3 m (10 ft) deep (Figure 2). The upper edges of the sinkhole are composed of unconsolidated LPQ Wash terrace alluvium approximately 2 m (6.5 ft) above channel elevation. Hairline tension cracks are apparent along the western edge of the sink which indicate further expansion of the sinkhole is likely. The base of the sink is chocked with large boulders with a discontinuous and unconsolidated sandy silt matrix. A fractured, fluted, and scalloped exposure of limestone is apparent in the southwestern wall of the sink (Figure 3). This exposure appears to be in situ and the textures are

![Figure 2. Detail view of La Posta Quemada sink at the time of this report. Aerial imagery was acquired by UAV on October 22, 2017.](image-url)
diagnostic of dissolution processes present in karst environments. Roots from nearby mesquite trees extend along gaps in the outcrop to unknown depths (Figure 4). A number of smaller sinkholes, caves, and suspected karst features are located on the hillslopes in the vicinity of LPQ sink on both sides of LPQ Wash.

The surface expression of LPQ sink is located within a low alluvial terrace adjacent to LPQ Wash and the base of the sink is below channel elevation. The extent of the underground void or fracture network associated with the sink is unknown but surface observations suggest it is significantly larger than the current surface expression of the sink. LPQ sink intercepts some surface flow in LPQ Wash, and has been observed to fill and drain hours or days following flow in the wash. At times, the boulders at the base of the sink are draped with mud following draining of the sink. Sidewall collapse and piping erosion incrementally widen the sink and fill in the base. When the sink fills with water and sediment and then subsequently drains, much or all of this sediment is flushed to unknown depths. Observed infiltration of surface flow in LPQ Wash upstream of LPQ sink is further evidence that a subsurface fracture or void network connected with the sink may be present in LPQ Wash.

![Image](image-url)

**Figure 3.** View of apparent in situ carbonate bedrock exhibiting dissolution textures in southern wall of LPQ sink. The base of the sink is filled with jumbled boulders with fine sediment draped on top and forming a discontinuous matrix in between. Field of view is approximately 2.5 m (8 ft). Photo taken on December 6, 2017.
History and growth of La Posta Quemada sink

Initial collapse observed at LPQ sink occurred in October 1994 along the western edge of LPQ Wash. Slumping and collapse of sandy channel alluvium and bubbles rising through slow moving channel flow were observed (personal communication, Bill Peachey, June 15, 2017). The slumped area was subsequently filled by channel sediment but a darker saturated zone in the area of the collapse persisted the following day after surface flow had waned. At this time, access to La Selvilla picnic area and campground was by way of a small paved road on the terrace above LPQ Wash. Collapse and subsequent filling in the same area of LPQ Wash was observed over the next several years and some unsuccessful attempts were made by park personnel to divert flow away from the area of collapse. By 1997 the collapsing area expanded to the northwest beneath the adjacent terrace until the access road was threatened. By 2005 the access road was undermined and collapsed into the sinkhole. Vehicle access to La Selvilla campground was detoured into LPQ Wash to avoid the sinkhole and a fence was installed around LPQ sink to prevent access. From 2005 until approximately 2016 the extent of LPQ sink was somewhat stable but an active July 2017 monsoon season resulted in expansion of LPQ sink beyond the fenced area. Today LPQ sink lies mostly within a fenced area but near-surface collapse, piping erosion features, and suspicious pothole collapse and slump features are evident outside the fenced area.

Figure 4. View of apparent in situ carbonate bedrock exhibiting dissolution textures in southern wall of LPQ sink. Large taproots from nearby mesquite trees extend to unknown depths within a limestone fracture exhibiting dissolution textures. Field of view is approximately 1.5 m (5 ft). Photo taken on December 6, 2017.
area on the stream terrace and low hillslopes near the sink. These features indicate the extent of the underground void network is greater than the current surface expression of the sink.

Components of La Posta Quemada sink study

In order to perform a comprehensive, non-invasive study of LPQ sink AZGS combined surficial surveying and mapping methods with subsurface remote sensing studies. By employing a multidisciplinary approach to this problem we hope to complement the strengths and minimize the uncertainty of each method. This investigation can be broken down into five separate components (Figure 5). A brief description of each part of this study is included below.

1. Surficial mapping with an emphasis on characterizing surface features that may be associated with subsurface voids.
2. Unmanned aerial vehicle (UAV) photo survey and digital elevation model (DEM) creation using structure from motion (SfM) techniques.
3. Combined lidar analysis of the LPQ sink area using existing Pima County lidar data and collection of new terrestrial lidar data at and adjacent to LPQ sink.
4. Microgravity and precision GPS survey in LPQ Wash centered on LPQ sink.
5. Electrical resistivity void mapping adjacent to LPQ sink and following the wash above and below the sink.

Surficial mapping of the La Posta Quemada sink area

AZGS has been actively involved in mapping surficial deposits and geologic hazards for more than 40 years. Most AZGS maps are 7 ½' quadrangle maps produced at 1:24,000 scale. In fact, the LPQ sink study area lies within an area mapped previously by AZGS (Richard et al., 2001). However, due to the much smaller study area, and to best characterize the geologic setting and delineate potential signs of collapse in the area around LPQ sink, AZGS conducted new detailed surficial mapping of the area at 1:1,000 scale. Mapping of the LPQ sink study area was conducted by Joseph Cook with assistance and feedback from Brian Gootee and Johnny Lyons-Baral. Emphasis was placed on delineating potential signs of collapse in the vicinity of LPQ sink and improving bedrock outcrop mapping not present on existing smaller scale maps. The limits of the mapping area for this study were based on the overall extent of all parts of the LPQ sink study and include areas well outside the immediate vicinity of LPQ sink. The resulting geologic map is an irregular polygon approximately 300 m (1000 ft) by 150 m (500 ft) oriented roughly northeast-southwest centered on LPQ Wash (Plate 1).

UAV structure from motion mapping

An unmanned aerial vehicle (UAV), also known as drone, was used to collect aerial imagery and develop a 3D model of LPQ sink. The model was, in turn, combined with other data sets, surficial mapping, GPS control, micro-gravity, and terrestrial LiDAR to help interpret the setting and geologic relationships in the study area. Overlapping aerial imagery collected by the drone can be used to model
horizontal and vertical terrain using a method called stereogrammetry or Structure-from-Motion (SfM). We used software (Agisoft Photoscan Professional) and its algorithms to build a 3D model of LPQ sink. High-precision GPS was used for ground and terrain control which resulted in aerial imagery of about 1 to 2 cm horizontal resolution and 4 cm vertical terrain resolution. Although the area is moderately vegetated the UAV survey component helped to identify subtle differences in color, terrain, vegetation, and overall morphology. The orthorectified photomosaic was also used to delineate the extent of some bedrock outcrops in the geologic map.

Detailed results and statistics for the UAV model are available in Appendix A.

**Lidar analysis**

Lidar is a laser scanning light detection and ranging technique (LiDAR) used to make high-resolution elevation and topographic maps. Distance to a target is determined using pulsed laser light and measurement of the reflected pulses with a sensor. The result of a lidar scan of an area is a 3-D point cloud model of the landscape. Lidar data can be collected via aircraft (airborne lidar/ALS) or from a tripod (terrestrial lidar/TLS). Depending on the point cloud density, a highly accurate digital elevation model (DEM) or digital terrain model (DTM) can be created. Subsequent lidar scans of the same area can be compared to detect change. Fortunately, multiple generations of airborne lidar covering the study area were flown by Pima County in 2005, 2008, and 2015 (Figure 6). As part of this study, additional terrestrial lidar scans of the immediate area surrounding LPQ sink were conducted to establish accurate
limits to the current surficial extent of the sinkhole. Leica Geosystems donated the use of a Leica MS60 multistation (a combined total station and laser scanner) for this project. Co-registering the datasets to a single spatial coordinate system datum is necessary for accurate change detection when using data based on older datums and/or local surveying ground control points. The final datum for this project was NAD83 UTM 12N metric, but with small-scale translations of the 2017 TLS and 2008 ALS data to the 2015 ALS terrain data as the datum.

Detailed statistics and metadata for the lidar study are available in Appendix B.

**Microgravity survey**

Microgravity surveys are a geophysical method that measures minute changes in the force of earth’s gravity. Local perturbations in the gravity field reflect the underlying geological structure. Because the density difference between empty void space and sediment or solid rock is significant, microgravity surveys are commonly used to detect the presence of underground voids. Gravity surveys have been successfully used to detect voids in geologic settings similar to the LPQ sink study area at Kartchner Caverns State Park and other cavern and karst systems outside Arizona. One of the benefits of gravity surveying is that it is non-invasive and non-intrusive. If a sinkhole or underground cavern has sufficient void volume to be detectable by gravity surveying, then the data can be used for safety planning and mitigation of the potential hazard. Conversely, if no significant underground void is detected this information is also useful for delineating known hazards associated with surface collapse features. A microgravity study including approximately 150 gravity stations in three parallel lines forming a grid along LPQ Wash was performed by J.B. Fink LLC. Gravity and GPS data collected in the field was subsequently processed, modeled, and interpreted to create gravity and elevation profiles in the wash adjacent to LPQ sink.

A detailed explanation and interpretation of the microgravity survey is available in Appendix C.

**Electrical resistivity void mapping**

Electrical resistivity is a geophysical method consisting of a linear line of equidistant sensors that measure the resistance of electrical current flow within a medium. Underground voids may be detected in this manner by measuring the contrast in resistivity between native sediments, bedrock, and air-filled voids. Air-filled voids are highly resistive features whereas the transmitted electrical current is propagated more readily through minerals in rocks and fine-grained soil. Void detection is affected by a number of factors including composition of the surrounding material, depth to the void, and whether the void is air-filled or filled with a combination of air, water, and sediment. For this study AZGS contracted with HydroGeophysics Inc to conduct a two-line electrical resistivity study along LPQ Wash centered on LPQ sink. Each line was 247 m (820 ft) long with electrode spacing of 3 m (10 ft). Resistivity data was collected over two days on 1/09 – 1/10/2018. Measured resistivity values were then processed and modeled to produce a plot of resistivity along the line profile.

A detailed description of the method and results of the resistivity study are available in Appendix D.
Results of geologic mapping, aerial photo comparison, and interpretation of LiDAR data

Because the collapse of LPQ sink is a relatively recent phenomenon we were able to analyze multiple generations of high resolution aerial imagery to bracket when noticeable change has occurred. The same principle applies to the two generations of airborne lidar. Comparing datasets from before and after a change in the landscape is useful to help focus on certain areas that might not otherwise appear remarkable on the ground. Comparison of the 2008 and 2015 airborne lidar data reveals noticeable change in the extent of LPQ sink (Figure 7). This is not surprising based on the known history of collapse and expansion of LPQ sink and is good confirmation for the timeline of these observations.

While comparing the airborne lidar datasets another possible collapse feature near LPQ sink was discovered. This feature is much larger in the landscape, 70 m (230 ft) by 30 m (100 ft), and is located on the slope above LPQ sink (Figure 7). Because the Arizona Trail crosses this feature it is informally named and referred to in this report as the AZT sink. Unlike LPQ sink there are no abrupt vertical walls along the margins of the feature but there are a number of other characteristics that suggest this feature may be a broad zone of collapse. The AZT sink is much wider than natural drainages observed elsewhere on the hillslope. On the ground this feature is a broad depression with inconsistent slope that captures surface drainage from all sides. The uppermost section of this feature is bound by very steep slopes not found anywhere else on the hillslope. Above this steep slope or scarp the drainages appear similar to those...
found elsewhere on the hillslope outside the AZT sink. Hillslope gradients within this feature alternate from very steep in the upper areas to nearly flat whereas gradients for typical channels elsewhere on the hillslope are relatively constant. Surface flow captured by the broad depression forms a series of small sandy to gravelly plunge pools in the upper reaches and takes a convoluted path through chaotic bedrock outcrops and jumbled boulders in the lower reaches of the feature before exiting through a narrow colluvial notch 25 m (80 ft) upstream of LPQ sink. Bedrock, where it is exposed within the feature, is dominantly very large in situ carbonate benches, piled boulders, or breccia clasts from outcrops above. Because surface flow on the hillslope is captured by AZT sink, vegetation within is densely spaced and larger than the same species outside the depression. If this depression is indeed another karst collapse feature, water captured by the depression is presumably dissolving more of the underlying carbonate bedrock, enhancing dissolution and collapse along existing voids, faults, and fractures.

Existing geologic mapping of the LPQ sink area includes 1:48,000 (Drewes, 1977) and 1:24,000 (Richard et al., 2001) scale mapping. The Drewes map predates surface collapse of LPQ sink and the sink is not shown on Richard’s map. Both maps are drawn at a coarse scale relative to the LPQ sink area and detailed bedrock outcrops on the hillslopes above LPQ sink and geomorphic relationships between hillslope colluvium, fluvial terraces, and channel deposits are not the focus of either map. Mapping

Figure 7. Surface change map based on 2008 and 2015 Pima County airborne lidar. Collapse at LPQ sink is evident and the possibility of a larger AZT collapse feature was observed. Possible smaller collapse features were noted nearby and later field-verified.
conducted for this project revealed hillslope colluvium in the LPQ area is thin and discontinuous and a large portion of the hillslope above the sink is actually exposed limestone and carbonate rocks (Figure 8). Determining bedding or fracture patterns of the limestones proved difficult as many of the discernable attitudes were inconsistent even over a short distance. Although abundant bedrock outcrops are present at or very near the surface on the slopes above LPQ sink and across the possible AZT sink, there does not appear to be a consistent measurable bedding or fracture pattern that would provide insight into determining the limits of likely collapse around either feature. These observations match those of Brod (1987) who described strike and dip measurements of limestone in the vicinity of colossal cave as “non-systematic, randomly-oriented, with relatively large dips”. Extensive faulting, both large- and small-scale folding, and shearing have all contributed to fracturing the underlying rocks in the LPQ sink area. The same solutional enlargement of voids along faults, joints, and fractures in carbonate rocks in and around Colossal Cave (Brod, 1987) occurs in the carbonates around LPQ sink.

LPQ sink is located within a low fluvial terrace adjacent to LPQ Wash. The base of the colluvial and bedrock slope is located immediately outside the fence surrounding the sinkhole on the northwest side. The original paved road leading to La Selvilla campground is located here along the base of the slope. A large portion of the road has collapsed into the sink rendering it impassable. Hairline cracks and open voids were observed along the western edge of LPQ sink. Voids continue in the subsurface beyond the southwestern portion of the fenced area and beneath a very large split boulder just outside the fenced area. These features appear prominently in the terrestrial lidar data. Aside from the small portions of this area that have already collapsed into the underlying void, the surface appears intact although in reality there is only a thin crust of surface soil extending over a shallow 2 m (6 ft) deep void. Additional anomalous depressions, slumps, tilted trees, and piping features were observed along the base of the slope up to 8 m (26 ft) outside the LPQ sink fenced area.

Although not in close proximity to LPQ and AZT sinks, other potential collapse features on the opposite side of LPQ Wash were noted in the airborne lidar data (Figure 7). A steep rocky drainage enters the southern side of LPQ Wash about 35 m (115 ft) downstream of where the La Selvilla access road enters the wash. There are two areas along this drainage that appear to exhibit anomalously steepened areas or depressions in the lidar data. Field verification of these features confirmed they appear to be incipient sinkholes within the craggy carbonate bedrock slope. In addition to these small collapse features, there are two known living cave systems within the hills to the southeast. Arkenstone and La Tetera caves are living caves not accessible to the public. The presence of these additional karst features in the vicinity of LPQ sink illustrates the complexity and extensive cavernous nature of carbonate rocks in the area.

The terrestrial lidar clearly measured the visible surface expression of LPQ sink and captured subtle details outside the main collapse area. LPQ sink was scanned from two close proximity locations on opposite sides of the rim. Even with these close and elevated perspectives, data shadows were
unavoidable due to the steep and fractured walls and boulder-chocked base of the sink. However, the angles of data capture did result in imaging of dark and narrow subsurface voids and conduits which appear to connect with nearby collapse features outside the fenced area. These shallow subsurface void networks are only covered by a thin ceiling or bridge of surface soil and are susceptible to collapse.

Based on surface observations, mapping, and lidar analysis, the current extent of surface collapse of LPQ sink can be delineated. In addition, a secondary area of suspected collapse features can be combined with the known collapse area to delineate a larger area of potential future collapse (Figure 9). These surface observations are only valid at the present and new telltale collapse features outside this expanded zone may develop at any time. In either case, LPQ sink appears to be expanding to the southwest mostly within the low terrace adjacent to LPQ Wash. There are some small erosional piping features and slumps apparent on the lowermost slope adjacent to the terrace but the largest voids and obvious expansion of the collapsing area is within the terrace. Because the terrace is heavily vegetated by mesquite, shrubs, and grasses, it is possible that existing underground voids similar to those near the fenced area are present but not yet visible at the surface. The microgravity and electrical resistivity study results in the following sections describe the available subsurface observations.
Results of microgravity survey

The microgravity survey conducted within LPQ Wash adjacent to LPQ sink combined high-resolution GPS data and gravity measurements. J.B. Fink LLC measured gravity along three profiles in LPQ Wash centered on LPQ sink. Processing and modeling of the measured gravity data did not reveal any low-density features that could be interpreted as underground voids anywhere in all three profiles even immediately adjacent to LPQ sink. Interpretation of these results indicate the limits of collapse of LPQ sink into an underground void do not project beneath LPQ Wash near the sinkhole (Appendix C). Based on the gravity data alone, there is no evidence for an imminent threat of collapse to vehicular or foot traffic in LPQ Wash in the surveyed area. (Figure 10).

Figure 9. Distribution of slump and collapse features observed along the base of the slope near LPQ sink and extent of strongly resistive features interpreted as underground voids in the resistivity data. The extent of the expanded collapse zone and interpreted underground voids serves as an estimate of the area around LPQ sink that may be prone to continued collapse.
A caveat to this conclusion is that it is possible the bedrock underlying LPQ Wash is fractured and faulted and hosts a complex network of small sediment- or air-filled voids which are not detectable by this survey. Richard’s 2001 map depicts faults between carbonate units which most likely connect across LPQ Wash but are masked by hillslope colluvium and young channel deposits. Based on observations of surface flow infiltration and repeat collapse of wash sediment near fenced LPQ sink it seems likely that some void network must be present. Detection of these small voids is made difficult because they become filled with channel sediment shortly after collapse. A detailed interpretation and description of each profile is available in Appendix C.

Figure 10. From Appendix C, pages 9-10. Calculated Bouguer gravity anomaly (CBA) profiles in LPQ Wash centered on LPQ sink. These profiles and the data plotted are described in detail in Appendix C. The absence of any downward deflection in the vicinity of LPQ sink implies there is no open underground void beneath LPQ Wash adjacent to LPQ sink.
Results of electrical resistivity survey

Two lines of resistivity data were collected near LPQ sink. Line 1 was placed along LPQ Wash and line 2 along the base of the slope above the wash adjacent to LPQ sink. Both lines were centered on LPQ sink. Overall, data quality for each survey line was high and required minimal removal of noisy data. The data were then run through an inversion model and plotted as 2D resistivity profiles (Figure 11, Appendix D). HydroGeophysics Inc.’s interpretation of the resistivity profiles identifies zones of “moderately increased resistivity compared to background” in LPQ wash in the vicinity of LPQ sink and several “strongly resistive zones” along the base of the slope near LPQ sink and farther upstream (Appendix D, pages 13-14). Strongly resistive zones are interpreted as underground void space whereas the moderately resistive zones are interpreted as potential underground voids that may be filled with fine-grained material or smaller, partially connected fracture networks. In addition to strongly resistive zones, several conductive features were observed and are interpreted as possible older collapses infilled with conductive clays, or moisture along a fault or fracture zone.

The contrast between the highly resistive zone below LPQ sink on line 2 and the lack of an equally highly resistive corresponding feature in LPQ Wash on line 1 suggest open underground voids associated with LPQ sink extend farther to the southwest beneath the vegetated alluvial terrace but not very far under LPQ Wash to the east (Hydrogeophysics Inc, Appendix D). Another resistive zone imaged in both line 1 and line 2 profiles is found upstream of LPQ sink beginning approximately where the road to La Selvilla campground climbs back out of LPQ Wash. This region roughly aligns with the possible AZT sink upslope to the northwest. Another resistive body was found toward the upstream end of line 2 where the road to La Selvilla campground again crosses LPQ Wash (Figure 12). Depth to interpreted void space in line 2 near LPQ sink is approximately 1-1.5 m (3-5 ft). Depth to interpreted void spaces elsewhere in the study area ranges from approximately 2-5.5 m (7-18 ft). A detailed interpretation and description of each profile is available in Appendix D.

Combined results of this study

Each component of this study has certain advantages and deficiencies. By combining observations and interpretations made across multiple methods we are able to confirm subtle observations made in one portion of the study with data from another. For example, small piping and slump features observed in the surface mapping portion of this study were thought to be possible indicators that the extent of collapse around LPQ sink is significantly larger than the fenced area and zone of obvious collapse. This idea was given additional support by the terrestrial lidar and electrical resistivity portions of this study that demonstrated voids extended below these telltale surface features underground. The possible AZT sink was initially identified in the airborne lidar analysis and later confirmed through field observations. Additional support for the presence of additional subsurface voids in the vicinity of LPQ and AZT sink was one result of the resistivity survey.
Electrical resistivity profiles for lines 1 & 2

Figure 11. Modified from Appendix D, page 12. Modeled electrical resistivity profiles for line 1 and 2 along LPQ Wash and along the base of the slope behind LPQ sink.

Legend
- Electrode Locations

La Posta Quemada Resistivity Profiles

Date: Jan 2018

2D Inverted Resistivity Plots

HGI Hydrogeophysics

Electrical Resistivity Void Mapping at La Posta Quemada Wash

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The current extent of surface collapse of LPQ sink is smaller than the extent of underground voids which ultimately determine the collapsible area. Based on surface and geophysical observations and data, we can expect ongoing collapse at LPQ sink may proceed along the base of the slope and within the vegetated alluvial terrace nearly to the road detour into LPQ Wash south of the current sinkhole and fenced area. Some of this collapse has already begun as evidenced by surface material collapsing into voids underneath and around the large split boulder just south of the fenced area.

The area surrounding LPQ sink is composed of faulted and fractured limestone and carbonate rocks. Any fault or fracture networks present in carbonate rocks provide possible pathways for dissolution and karst processes. This is especially true along LPQ Wash which reliably flows following rainfall. Simply put, the geologic setting of the LPQ sink area is conducive to karst-forming processes. We are aware of several large caves, probable collapse at AZT sink, and many small karst collapse features in the vicinity of LPQ sink. The conclusions drawn from the resistivity study demonstrate there are additional underground voids that lack surface expression. Low resistivity features interpreted as prior collapse zones or fault or fracture networks provide infiltration points for surface flow in LPQ Wash. Observations of disappearing surface flow along several reaches in LPQ Wash support this possibility.

Recommendations

Quantifying the hazard of karst collapse in the vicinity of LPQ sink to park visitors is difficult. Collapse at LPQ sink has been ongoing for more than 20 years but most collapse has been incremental and closely associated with flow in LPQ Wash. Both the resistivity and gravity surveys conclude there does not appear to be a significant void adjacent to LPQ sink within LPQ Wash. Extrapolating on the observed collapse history of LPQ sink and based on the surface observations and resistivity data from this study, it seems plausible that incremental collapse coinciding with the summer monsoon and winter rainy seasons will continue outside the fenced area along the base of the slope and within the vegetated alluvial terrace to the southwest of the fenced area. The limits of the main portion of LPQ sink are plainly visible to any observer and relatively easy to avoid. However, a less-obvious hazard is present around the margins of the main sink which have not yet collapsed. Collapse of surface material into underlying voids may occur at any time and is particularly likely if weight is applied to a thin, unsupported soil bridge or surface material loosely supported by roots. Restricting access to the entire alluvial terrace and lower portion of the slope above the terrace and currently fenced area is recommended to minimize the hazard to park visitors.

Although no surface expression of collapse was observed upstream of LPQ sink along LPQ Wash, the resistivity data show possible underground voids in several areas. These voids are interpreted to exist at greater depths and may consist of smaller or less continuous open void space than LPQ sink based on their measured resistivity. There are a significant number of known caves, underground voids, and karst collapse features in the area. It is likely many of these voids have been present underground in some extent for thousands of years and may not break the surface for thousands more. Existing voids along LPQ Wash, however, likely constitute a higher risk of collapse due to more rapid dissolution by relatively frequent flow in the channel and greater stress applied at the surface by vehicle access to the campground. If underground voids or void networks do exist upstream of LPQ sink, ongoing dissolution processes similar to those observed at LPQ sink are occurring at these locations as well. Close monitoring of any slumping, appearance of surface cracks, or incipient collapse along any part of the
road to La Selvilla campground along LPQ Wash should be performed, especially during the rainy seasons.

Figure 12. Distribution of underground voids interpreted in electrical resistivity data relative to known surface collapse features. The subsurface features northeast of LPQ sink have no surface expression. These features are less-resistive than the void detected at LPQ sink and may be smaller, partially filled with dry debris, or less continuous.
References


Map Unit Descriptions

Alluvial units

- Active channel deposits - Active Posta Quemada Wash deposits are unconsolidated, very poorly sorted sandy to cobbly beds exhibiting bar and swale microtopography. Clasts vary lithologically but consist mostly of sub-rounded to angular carbonate rocks, conglomerates, breccias, and granitoids. Qycr deposits are typically unvegetated to lightly vegetated on in-channel bars and exhibit no soil development. Qycr deposits are entrenched up to 2m (6 ft) or more below adjacent Qy2 and Qy3 terraces. Some of these deposits are submerged by the low-flow channel and the remaining areas are submerged during higher seasonal or extreme flow events. These areas are subject to deep, high velocity flow and lateral bank erosion.

- Young fluvial terrace deposits - Young fluvial terrace deposits located adjacent to La Posta Quemada active channel deposits. Qy3 terraces are composed of unconsolidated sand to boulders and may be lightly vegetated. Qy3 terraces stand slightly higher (0.25 - 0.5m) in the landscape than Qyc deposits.

- Young fluvial terrace deposits - Young fluvial terrace deposits located adjacent to La Posta Quemada active channel deposits and Qy3 terraces. Qy2 terraces are composed of unconsolidated silt, sand and cobbles although they are dominantly fine-grained at the surface. Qy2 terraces are often more densely vegetated than younger deposits. Vegetation includes large mesquite, cattail acacia, prickly pear, and cholla. Qy2 terraces stand moderately higher (0.5 - 2m) in the landscape than Qyc deposits.

- Talus and colluvium - Unconsolidated talus and colluvium found on steep hillslopes below bedrock outcrops. Clast size ranges from coarse sand to very large boulders. A thin (< 1m) colluvial cover mantles underlying bedrock on slopes throughout the study area. In situ bedrock outcrops are found where the colluvium cover is discontinuous or especially thin. Soil development is absent to weak on Qtc deposits but some soil reddening is observed where colluvium is thick and has been stabilized by vegetation. Qtc deposits are moderately vegetated by mesquite, acacia, palo verde, saguaro, cholla, prickly pear, and grasses.

- Paleozoic carbonate rocks, undivided - Undivided carbonate bedrock which may include Pennsylvanian Horquilla, Mississippian Escabrosa, Permian Concha limestones, and Devonian Martin dolostone. These carbonate rocks were mapped nearby in AZGS DGM-12 (Richard et al., 2001).

Bedrock

- Paved and dirt road used to access La Selvilla campground and nearby private residence outside the study area.

Sinkhole

- Unconsolidated boulders and alluvium which have collapsed into the La Posta Quemada sinkhole. Separate collapse features on the surface are connected to the same void network in the subsurface. Point collapse features identified nearby may also be related to the same void network.