ELECTRICAL RESISTIVITY VOID MAPPING AT
LA POSTA QUEMADA WASH

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1.0 INTRODUCTION

1.1 PROJECT DESCRIPTION

In January 2018, hydroGEOPHYSICS, Inc. (HGI), under contract to the Arizona Geological Survey, completed an electrical resistivity survey in La Posta Quemada (LPQ) wash located in Colossal Cave Mountain Park. The site was near a visible sinkhole (La Posta Quemada Sinkhole) which collapsed under the road to La Selvilla Picnic Area. The objective of the geophysical investigation is to further define the subsurface extent of the sinkhole using the electrical resistivity method.

1.2 SITE LOCATION

La Posta Quemada Wash is located in Southern Arizona, U.S.A., approximately 6 miles northeast of Vail, AZ (Figure 1). The survey area crossed the Vail and Rincon Peak 7.5’ USGS topographic maps.

1.3 OBJECTIVE OF INVESTIGATION

The objective of the geophysical investigation is to evaluate whether subsurface voids exist beyond the extent of the 20’x 20’ footprint of the La Posta Quemada sinkhole. The surface expression of the sinkhole has been expanding since the 1990s and there are concerns regarding future collapses of the sinkhole in the surrounding basin.

Electrical resistivity geophysical characterization of the subsurface measures how well various earth materials conduct electricity through either electronic or electrolytic (pore water) means. In the case of void detection, the targets for the electrical resistivity survey would be regions of high resistivity (low conductivity) based on the assumption that air-filled void space would have increased resistivity compared to the native alluvial or bedrock material because air acts as a poor conductor.
2.0 BACKGROUND

2.1 GEOLOGY

Colossal Cave Mountain Park sits on the western flank of the Rincon Mountains to the east of Tucson, AZ. The bedrock geology of the park and project location is predominately Paleozoic sediments which have been heavily faulted, folded, and fractured in numerous tectonic events (heavy black lines on overlain geologic map by Drews, 1977. Figure 2). The sedimentary units include several limestone, dolomite, and marlstone layers including the Concha Limestone, Epitaph Dolomite, Colina Limestone, Horquilla Limestone, and Escabrosa Limestone (areas shown in blue hues in Figure 2). The fracturing of these carbonate units has allowed for heightened fluid flow and dissolution creating Karst topography in the area with abundant pockets, caves, and other voids, including the Colossal Cave network. Surface erosion has since exposed some of these void networks as evidenced by the La Posta Quemada sinkhole (Figure 3).
Figure 2. Geology of La Posta Quemada Wash.

Figure 3. La Posta Quemada Sinkhole.
2.2 LIDAR SCAN

Pima County completed a Light Detection and Ranging (LIDAR) scan of the area prior to the electrical resistivity investigation. The LIDAR map was used to refine the positioning of the electrical resistivity lines and identify locations of deformation around La Posta Quemada Canyon. The LIDAR method uses a laser to measure variable distances to the Earth, thus determining features that may have shifted – in this case, sunken ground in La Posta Quemada Canyon. The LIDAR scan (as delivered to HGI by the AZGS) is shown below in Figure 4.

In the hill shade produced by the AZGS, the current extents of the La Posta Quemada sinkhole are evident (labeled as “PQ Sink” in the image). Other hill slope anomalies are also noted on the image, which may indicate other potential collapse type features (e.g.: the bracketed “?” on the image), and the deep drainages that are relatively symmetrical on either side of the main wash.

3.0 METHODOLOGY

3.1 SURVEY AREA AND LOGISTICS

Two lines of resistivity data were acquired in the project area, with survey parameters as detailed in Table 1 (coordinates in UTM meters, zone 12N). Figure 5 shows detailed resistivity survey coverage for the two lines of resistivity with the electrode points labeled for reference.

Geophysical cables with eighty-four stainless steel electrodes spaced at a maximum of 10 feet (3m) were used along with an Alt-3 Wenner array (Cubbage et al., 2017) for acquisition of the electrical
resistivity data. The Alt-3 Wenner array was used to gather the maximum amount of data given the electrode spacing and allow for flexibility and optimization in data processing.

### Table 1. Resistivity Survey Details

<table>
<thead>
<tr>
<th>Line Name</th>
<th>Date(s) of Acquisition</th>
<th>Line Length</th>
<th>Line Start</th>
<th>Line End</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 1</td>
<td>1/9/18</td>
<td>820 feet (247 meters)</td>
<td>535015 E, 3547100 N</td>
<td>535168 E, 3547294 N</td>
</tr>
<tr>
<td>Line 2</td>
<td>1/10/18</td>
<td>820 feet (247 meters)</td>
<td>535000 E, 3547146 N</td>
<td>535193 E, 3547290 N</td>
</tr>
</tbody>
</table>

### Figure 5. Electrical Resistivity Lines with Electrode Locations.

#### 3.2 ELECTRICAL RESISTIVITY

Electrical resistivity is a volumetric property that describes the resistance of electrical current flow within a medium (Rucker et al., 2011; Telford et al., 1990). Direct electrical current is propagated in rocks and minerals by electronic or electrolytic means. Electronic conduction occurs in minerals where free electrons are available, such as the electrical current flow through metal. Electrolytic conduction, on the other hand, relies on the dissociation of ionic species within a pore space. With
electrolytic conduction, the movement of electrons varies with the mobility, concentration, and the degree of dissociation of the ions.

Mechanistically, the resistivity method uses electric current (I) that is transmitted into the earth through one pair of electrodes (transmitting dipole) that are in contact with the soil. The resultant voltage potential (V) is then measured across another pair of electrodes (receiving dipole). Numerous electrodes can be deployed along a transect (which may be anywhere from feet to miles in length), or within a grid. Figure 6 shows examples of electrode layouts for surveying. The figure shows transects with a variety of array types (dipole-dipole, Schlumberger, pole-pole). A complete set of measurements occurs when each electrode (or adjacent electrode pair) passes current, while all other adjacent electrode pairs are utilized for voltage measurements. Modern equipment automatically switches the transmitting and receiving electrode pairs through a single multi-core cable connection. Rucker et al. (2009) describe in more detail the methodology for efficiently conducting an electrical resistivity survey.

Figure 6. Possible Arrays for Use in Electrical Resistivity Characterization

The modern application of the resistivity method uses numerical modeling and inversion theory to estimate the electrical resistivity distribution of the subsurface given the known quantities of electrical current, measured voltage, and electrode positions. A common resistivity inverse method incorporated in commercially available codes is the regularized least squares optimization method (Sasaki, 1989; Loke, et al., 2003). The objective function within the optimization aims to minimize the difference between measured and modeled potentials (subject to certain constraints, such as the type and degree of spatial smoothing or regularization) and the optimization is conducted iteratively due to the nonlinear nature of the model that describes the potential distribution. The relationship between the subsurface resistivity (ρ) and the measured voltage is given by the following equation (from Dey and Morrison, 1979):

$$-\nabla \left[ \frac{1}{\rho(x,y,z)} \nabla V(x,y,z) \right] = \left( \frac{I}{U} \right) \delta(x - x_s) \delta(y - y_s) \delta(z - z_s) \tag{1}$$

where I is the current applied over an elemental volume U specified at a point (x_s, y_s, z_s) by the Dirac delta function.
Equation (1) is solved many times over the volume of the earth by iteratively updating the resistivity model values using either the L_2-norm smoothness-constrained least squares method, which aims to minimize the square of the misfit between the measured and modeled data (de Groot-Hedlin & Constable, 1990; Ellis & Oldenburg, 1994):

\[
\left(J^T J + \lambda W^T W\right) \Delta r = J^T g - \lambda W^T W r_{i-1}
\]

or the L_1-norm that minimizes the sum of the absolute value of the misfit:

\[
\left(J^T R_d J + \lambda W^T R_m W\right) \Delta r = J^T R_d g - \lambda W^T R_m W r_{i-1}
\]

where \( g \) is the data misfit vector containing the difference between the measured and modeled data, \( J \) is the Jacobian matrix of partial derivatives, \( W \) is a roughness filter, \( R_d \) and \( R_m \) are the weighting matrices to equate model misfit and model roughness, \( \Delta r \) is the change in model parameters for the \( i \)th iteration, \( r_i \) is the model parameters for the previous iteration, and \( \lambda_i \) = the damping factor.

3.3 VOID DETECTION

The resistivity contrast between native material and subsurface voids will depend on a number of factors, including depth to voids, fill material of the void (air, groundwater, sediments, a mixture), dimensions of the void, and the composition of the surrounding native material. An example of a resistivity survey HGI performed looking for subsurface voids over the Kartchner Caverns State Park in Arizona (2007) is shown in Figure 7. The known air-filled voids, caverns, and passageways are highly resistive features, with values measured in 1,000’s (\( \log_{10} = 3 \)) to 10,000’s (\( \log_{10} = 4+ \)) of ohm-meters (ohm-m). In contrast, the surrounding limestone bedrock displays resistivity values measuring 100’s of ohm-m. There is a fair amount of variability in resistivity range depending on the dimensions of and depths to the subsurface voids. The high resistivity of the air-filled voids tends to mask the signal underlying the features, and it is difficult to interpret the character of the subsurface below these features to fully determine depth of voids.

Figure 7. Electrical Resistivity Profile over the Kartchner Caverns State Park, AZ.
3.4  EQUIPMENT

3.4.1  Resistivity Equipment

Data were collected using a Supersting™ R8 multichannel electrical resistivity system (Advanced Geosciences, Inc. (AGI), Texas) and associated cables, electrodes, and battery power supply. The Supersting™ R8 meter is commonly used in surface geophysical projects and has proven itself to be reliable for long-term, continuous acquisition. The stainless steel electrodes were laid out along lines with a constant electrode spacing (3 meters, or ~ 10 feet). Multi-electrode systems allow for automatic switching through preprogrammed combinations of four electrode measurements.

3.4.2  GPS

During field efforts, positional data were acquired via a handheld GPS; these data were used by the HGI field crew to record the location of survey lines and track survey progress, as well as produce model results.

3.5  DATA PROCESSING

3.5.1  Resistivity Data Editing

Following field data collection, the raw resistivity data files were transmitted to the HGI server located in Tucson, Arizona. The raw data were evaluated for measurement noise. Those data that appeared to be extremely noisy and fell outside the normal range of accepted conditions were removed. Examples of conditions that would cause data to be removed include: negative or very low voltages, high-calculated apparent resistivity, extremely low current, and high repeat measurement error. Overall data quality for this survey was high, with low repeat error and low occurrence of negative voltages, resulting in very little data removal per line (0% minimum to 6.7% maximum data removal during editing phase).

3.5.2  2D Resistivity Inversion

RES2DINVx64 software (Geotomo, Inc.) was used for inverting individual lines in two dimensions. RES2DINVx64 is a commercial resistivity inversion software package available to the public from www.geotomosoft.com. An input file was created from the edited resistivity data and inversion parameters were chosen to maximize the likelihood of convergence. It is important to note that up to this point, no resistivity data values had been manipulated or changed, such as smoothing routines or box filters. Noisy data had only been removed from the general population. The inversion process followed a set of stages that utilized consistent inversion parameters to maintain consistency between each model. Inversion parameter choices included the starting model, the inversion routine (robust or smooth), the constraint defining the value of smoothing and various routine halting criteria that automatically determined when an inversion was complete.
Convergence of the inversion was judged whether the model achieved an RMS of less than 10% within four to six iterations.

3.5.3 2D Resistivity Plotting

The inverted data were output from RES2DINvX64 and were gridded and color contoured in Surfer (Golden Software, Inc.). Electrode locations, line crossings, surface-based geologic field observations and other relevant features are plotted on the resistivity sections to assist in data analysis. Common color contouring scales are used for both of the lines to provide the ability to compare intensity of targets from line to line. Electrically conductive (low resistivity) regions are represented by cool hues (pinks to blues) and electrically resistive regions are represented by warm hues (reds to browns).

4.0 RESULTS & INTERPRETATION

This section presents the results of the geophysical survey. The resistivity inverse modeling results are presented in Figure 8, which shows the two survey lines oriented with the surface-breaching LPQ Sinkhole as a common reference point. Due to the highly variable nature of the electrical properties of the subsurface in this area, the profiles are presented with Log_{10} values for resistivity as the values range from nearly 0 to greater than 30,000 ohm-m. The lines and their resistivity profiles are described in greater detail below.

Depths on the cross sections are approximated with a 10-20% error in their absolute position based on the centroid of the target. The resistivity model transitions from resistive to conductive bodies, with the inflection between the two typically interpreted as the interface. The models positional accuracy however, can vary based on the relative strengths of the conductive/resistive signatures, and increasing depth to the feature.
Figure 8. Electrical resistivity profiles for lines 1 & 2
4.1 LINE 1

Line 1 runs up La Posta Quemada wash from SW to NE. It begins approximately 40 feet upstream of the sharp westerly bend in the wash course and is located predominately on the west side of the wash at the edge of the vegetated terrace. The main exclosure area for the LPQ sinkhole is 15 feet to the west of electrodes L1-029 through L1-032. Where the La Selvilla access road detours around the sinkhole and into the wash, the line runs in the center of the wash. Electrodes in the wash were dug into damp sand with red staining approximately 1.5 feet below surface. Due to the dry, loose nature of the wash material, contact resistance (a measure of how well the electrodes can communicate current into the ground) was higher than ideal, but the data collected on the line did not show high error or signal noise, and 86% of the data (6,012 data points) was used to run the resistivity models following raw data editing.

The resistivity profile shown in Figure 8 shows the resistivity of the subsurface below the line with electrode locations and surface features noted for reference. In general, the profile shows a thin near-surface conductive layer, underlain by more heterogeneous material. The current extent of the LPQ sinkhole and other related collapse features are approximately 30 feet to the west of electrodes 25-33, with the main chain-link area centered on electrode 30.

The thin conductive layer is interpreted as a 6-8 foot thick, clay-rich soil layer. Red soils were noted in the field in several areas in and around the sinkhole escarpment, extending down several feet to the top of bedrock.

In the region of the known sinkhole, below the conductive soil layer, there are areas of moderately increased resistivity compared to background, for example below electrode 25, approximately 15’ below the surface (+/- 3 feet). This feature measures approximately 10’ in length and is interpreted as representing a potential void space. Below this feature, the profile shows decreased resistivity, suggesting that the potential void area either does not extend to a great depth or may be filled with fine-grained material.

To the north of the cordoned-off sinkhole there exists a larger and more resistive body, located near the center of the profile from electrodes 40-45 (approximately 50’ in length), which is also approximately 15 feet below the surface. This reach is just upstream from where the road detour goes back up onto the established pavement. This body shows resistivity in the 1,000-4,000 ohm-m range and appears to be sharply bounded on both the south and north side. This body is interpreted as containing void space due to the highly resistive nature of the signal. The interconnectedness of the voids is not determinable by this means though. It is also difficult to determine the character of the formation below the resistive body due to the strong nature of the target, however it appears to be resistive as well.

Continuing to the north of the aforementioned high resistivity body, the subsurface resistivity is heterogeneous with lower magnitude resistive bodies at electrode 53 and potentially northward.
Below electrode 55, a conductive feature is noted deeper in the subsurface that may constitute a fracture of some type.

4.2 LINE 2

Line 2 begins on the La Selvilla access road, approximately 50 feet south of the detour around the sinkhole area and approximately 200’ north of the intersection of the Arizona Trail with the road. Electrodes on this line are predominately placed into the transition between colluvium and road grade, and run on the west side of the road. The line skirts the sinkhole exclosure to the west of the chain link fence between electrodes 22 and 25, and crosses LPQ wash from electrodes 61-65. The line passes downhill of another possible collapse feature (as denoted in Figure 4 as the bracketed area with a ‘?’) from electrodes 32-35.

The character of this line is similar to that of Line 1, with a thin conductive surface layer underlain by heterogeneous subsurface material. This line shows more strongly resistive bodies than Line 1.

The La Posta Quemada Sinkhole shows up strongly in the southern region of the resistivity profile as a highly resistive region underneath thin soils that is approximately 3-5 feet below surface in this area. Resistivity values exceed 30,000 ohm-m, and the feature appears to underlie the entire exclosure area. Just to the north of the LPQ sinkhole is a strongly conductive feature that appears to extend to depth; this could represent a feature such as an older collapse that has been infilled with conductive clays or moisture.

Heading north, the subsurface below electrodes 29-47 shows another strongly resistive zone 10-18 feet below surface (+/- 3 feet). Peak resistivity values in this area are approximately 3,400 ohm-m suggesting either very dry material, or the presence of air-filled voids. These features are less resistive than the LPQ sinkhole signal, suggesting that if they are voids, they are potentially smaller and not as interconnected, or filled with dry debris. The region below the bodies is also difficult to interpret due to the strength of the resistivity signal, but appears to be less resistive, and potentially more competent. Immediately to the north of these bodies (approximately electrode 48), is another downward-reaching conductive signal which could indicate either an older collapse that has been infilled by clays, a paleotopographic low also infilled by soil, or a through-going fracture/fault zone.

Line 1 and 2 cross on the northern end of the line, and both show similar subsurface character in these regions with a thin conductive layer in a small basin underlain by resistive material.

Below the wash, from electrodes 61-65 and extending to the edge of the cross-section, another large resistive body is noted approximately 7 feet below surface. This may be correlative with the resistive region seen in the northernmost portion of Line 1 in this area, although the strength of the signal is much stronger in Line 2. This body is also interpreted as being due to void space and may correlate with a depression noted in the LIDAR on the western hillside.
4.3 INTERPRETATION

The results of this study suggest that there are several potential voids in the subsurface of La Posta Quemada wash near the known sinkhole. The extent of the known sinkhole appears to extend to the south, but not much further to the east, as interpreted from a highly resistive feature imaged beneath the known location of the LPQ sinkhole on Line 2 and the lack of an equally high resistivity corresponding feature on Line 1. Other potential voids may be present to the north of the sinkhole, based on additional resistive features imaged. Figure 9 shows the resistive areas (potential void areas) noted in the resistivity profiles overlain on the plan-view coverage map as red polygons. The potential void areas appear to be roughly coincident with a broad-mouthed drainage to the north, potentially signifying another collapse feature is associated.

It is important to note that this geophysical method alone cannot for certain say that these resistive features are in fact voids, just that they are highly electrically resistive features in contrast to the surrounding material, which is the expected response of an air-filled void. And, while this method produces general spatial information for resistive targets, it is difficult to determine the nature of the resistive bodies, their fill, or to what depth they extend. Other investigation methods must be employed to validate the hypothesis; these methods include soil boring, drilling, trenching or other means of exposing the subsurface.

Figure 9. Resistive bodies of LPQ Wash
5.0 SUMMARY

hydroGEOPHYSICS, Inc. conducted an electrical resistivity survey in La Posta Quemada Wash in Colossal Cave Mountain Park, Pima County, AZ. The objective of the survey is to determine the extent of voids associated with a sinkhole that opened up in the road to the La Selvilla campground and picnic area. The survey was conducted using an 84-electrode array with a 10’ spacing between electrodes. The electrical resistivity technique employed herein identifies areas that are highly resistive to the flow of light electrical currents. Areas that are highly resistive in this setting potentially represent void space in the underlying bedrock due to the karst nature of the limestone. Interpretations of the resistivity profiles alone however do not necessitate there being voids, and other investigation methods must be employed to validate the hypothesis. These methods include soil boring, drilling, trenching or other means of exposing the subsurface.

Line 1 was run up LPQ wash to determine what the subsurface structure looked like below the current detour around the sinkhole. Line 2 ran between the sinkhole and the hill slope on the edge of the campground access road. Both lines show resistive bodies proximal to the LPQ sinkhole, and identify other resistive areas in the canyon as well (Figure 9). These resistive areas are interpreted as representing potential void spaces based on observations of the surrounding outcrops, the proximity to known karst topography (e.g.: the LPQ sinkhole and Colossal Cave itself.
6.0 REFERENCES


