Appendix C

31 January 2018

Microgravity survey in La Posta Quemada Wash adjacent to a sinkhole in Colossal Cave Mountain Park, Pima County, Arizona.

The following is a letter report of a microgravity survey performed alongside the known sinkhole in and adjacent to a portion of La Posta Quemada Wash within Colossal Cave Mountain Park. The field observations were conducted during December 2017 and January 2018.

The two goals of the survey were: 1. to ascertain any indication of a sufficiently large void whereby traffic to La Selvilla Campground might be impacted (i.e. hazard detection), and 2. if a void or voids were indicated to determine the subsurface extent of such voids to, presumably, allow some level of mitigation and-or avoidance.

Site Location: Colossal Cave Mountain Park (CCMP) is located in Pima County, Arizona approximately 20 miles southeast of the city of Tucson. Figure 1 below is a location map based on a shaded relief map of a portion of the CCMP around the sinkhole.

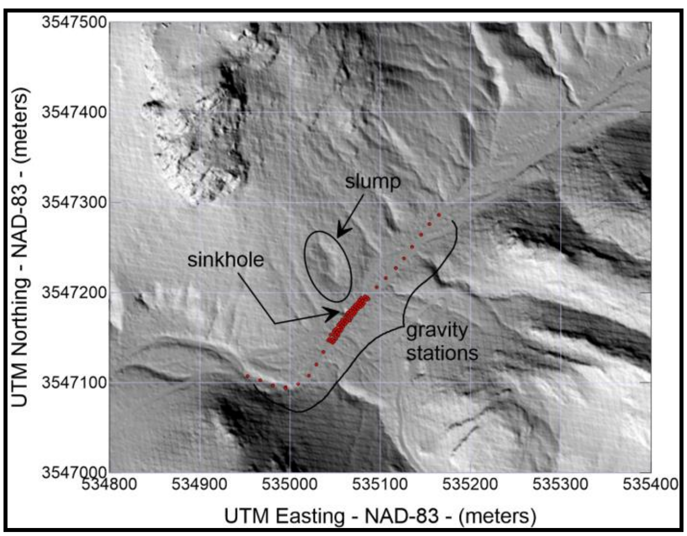

Figure 1. Shaded relief map of the area within CCMP showing the locations of the sinkhole, the microgravity survey stations (in red) and a possibly related slump.

Geology:

The relevant geology of the immediate area around the sinkhole will be covered by recent mapping by the Arizona Geological Survey. What is most relevant to the microgravity is the presence of a major fault along the axis of LPQ Wash. Although not formally recognized the presence of contrasting and opposing lithologies across the Wash belie its presence. This aspect of the geology is important in the interpretation of the microgravity data, particularly near the sinkhole.

Microgravity Instrument and Observations:

Line and station locations
Microgravity is defined by small spatial variations in gravity data associated with close-spaced observations. In this case the critical survey coverage was immediately adjacent to the sinkhole and consisted of three roughly parallel lines extending 100 feet north and south of the approximate center of the sinkhole (as projected into the Wash). Station interval was 10 feet (~3 meters) and line separation was 10 feet (~3 meters). The central line in the Wash was extended north and south of the sinkhole vicinity an additional 400 feet (~122 meters) at 50 foot (~15 meter) intervals. The resultant central line (Line 1) was 1000 feet (~305 meters) long. Station locations are indicated as red dots in Figure 1.

Local base station and quality control
To minimize loop time a brass cap monument was installed as a stable reference point in the abandoned road just north of the sinkhole. The cap is stamped with a station label of LPQ-001. Absolute gravity was not determined for LPQ-001. It is assigned an arbitrary gravity value of zero (for local relative gravity observations). It may be tied to any established station of known absolute gravity but for the purposes at hand its specific absolute value is not necessary.

Loop times ranged from a minimum of 73 minutes (~1.2 hrs) to a maximum of 242 minutes (~4 hrs). Average loop time was 160 minutes (~2.5 hrs). LPQ-Base was occupied a total of 17 times. Average occupation times for LPQ-Base observations was roughly 5½ minutes during which time a time-series of meter readings taken at one second intervals was recorded for subsequent processing. Average standard deviation for all LPQ-Base observations (after solid earth tide and drift corrections) was 2.4 µGals.

Gravimeter
The gravimeter used for the survey was a LaCoste & Romberg Model G, serial number 325. It has been upgraded by L & R Meter Service, LLC to their *LRFB-300 Feedback Upgrade* and *L and R Lithium-Ion Battery Upgrade*. The electronic upgrade increases the meter's resolution to 0.001 µGal (L and R Meter Service User's Manual, 2010) and allows the meter to record time series in an accompanying datalogger as opposed to single-valued, optical readings.

Survey period, stations and quality control
Gravity data were acquired on the following days: 12, 14, 18, 19, 22, 27 and 29 December 2017, and 2, 3, and 6 January 2018. A total of 80 unique stations were occupied with approximately 25% repeat observations (not including the base station). The average occupation time for each station was 3.4 minutes. The average standard deviation for all the time-series for all non-base-station observations was 2.3 µGal.

Observed gravity Line 1 (full length)

Observed gravity data result from converting gravimeter readings to values in gravity units, such as milligals (mGal) or microgals (µGal), by removing calculated solid earth tidal effects and correcting for instrumental drift. Observed gravity values (relative to the LPQ-001 base station) are presented for Line 1 in Figure 2.

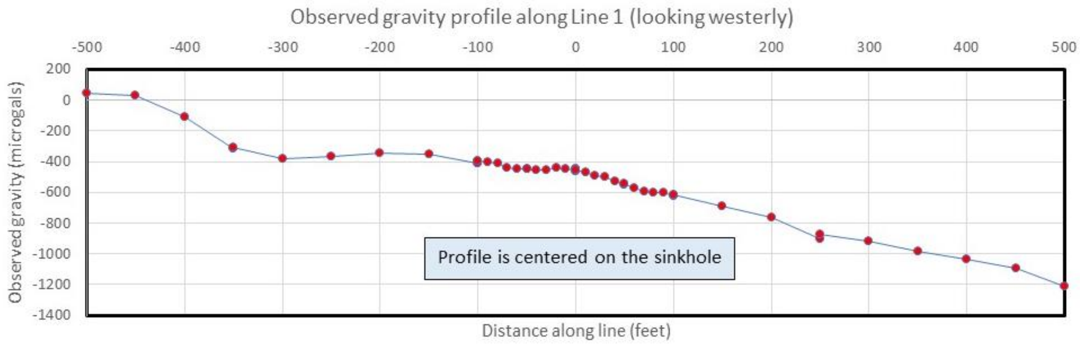

Figure 2 Observed gravity values for Line 1 full length, looking westerly.

In Figure 2 the right side represents the up-gradient (or northernmost) end of Line 1 and the left side the down-gradient (or southernmost) end. Line 1 essentially follows the center of LPQ drainage for the length of the profile. The increase in observed gravity from the up-gradient end to the low-gradient end is entirely a function of the decrease in elevation. Note that observed gravity, although influenced by elevation, has no elevation corrections or adjustments. Such corrections are discussed later. Maximum gravity difference from north to south is roughly 1200 µGal or 1.2 mGal. Notice the absence of any downward deflection in the vicinity of the sinkhole.

Observed gravity Line 1 (central portion)

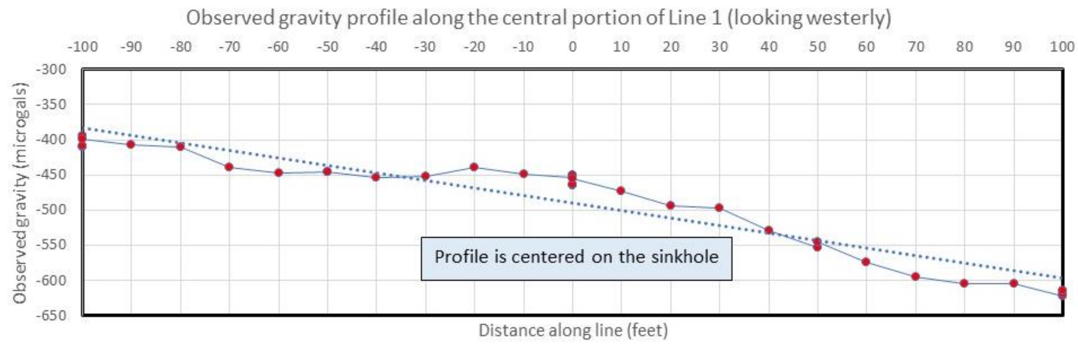

Figure 3 Observed gravity profile along the central portion of Line 1, looking westerly. The dotted line is a linear trend fit to the data for reference only.

Observed gravity Line 2

Observed gravity data for Line 2 are presented in Figure 4 at the same vertical and horizontal scales as in Figure 3. Line 2 was located 10 feet closer to the sinkhole relative to Line 1 and was parallel to Line 1. It remained just within the boundaries of LPQ Wash and, essentially, at the same elevation as Line 1. Line 2 was only surveyed for a length of 200 feet and, like Line 1, was centered at the sinkhole.

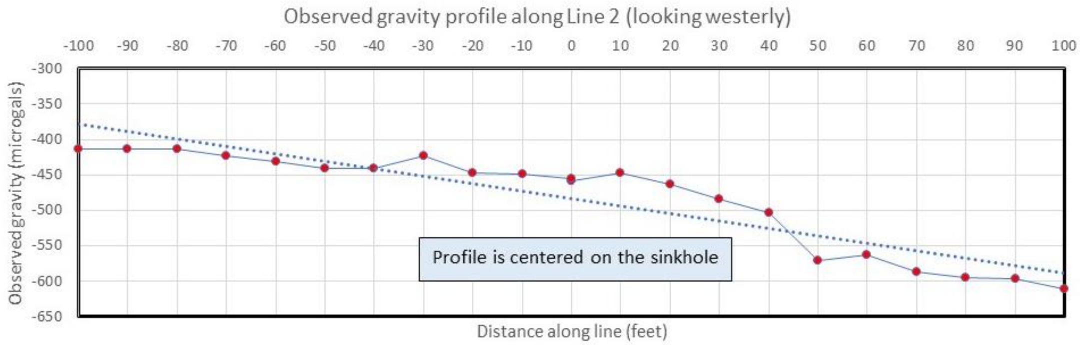

Figure 4 Observed gravity for Line 2, looking westerly. The dotted line is a linear trend fit to the data for reference only.

If the existing cavity representing the sinkhole were to have any influence on the gravity survey it should have been most noticeable at the center of Line 2 and would have resulted in a decrease in gravity values. No decrease is noted in the center of Line 2.

Observed gravity Line 3

Observed gravity data for Line 3 are presented in Figure 5 at the same vertical and horizontal scales as in Figures 3 and 4. Line 3 was located 10 feet further from the sinkhole relative to Line 1 and was parallel to Line 1. It remained just within the boundaries of LPQ Wash and, essentially, at the same elevation as Line 1. Line 3 was only surveyed for a length of 200 feet and, like Lines 1 and 2, was centered at the sinkhole.

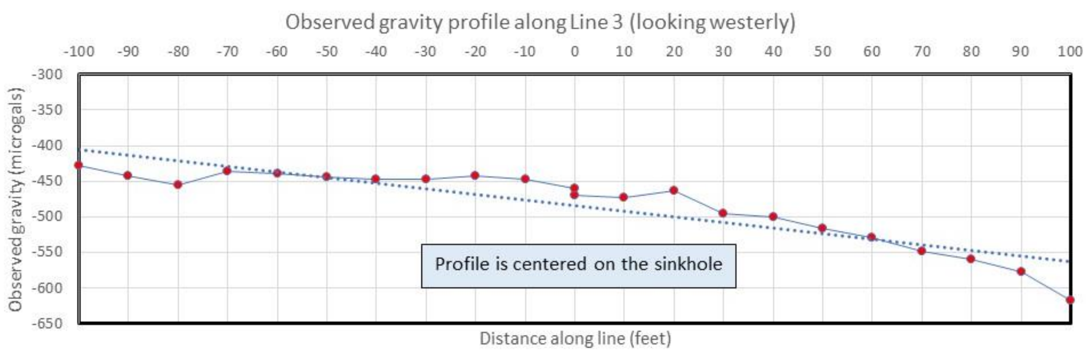

Figure 5 Observed gravity for Line 3, looking westerly. The dotted line is a linear trend fit to the data for reference only.

If the existing cavity representing the sinkhole were to have any influence on the gravity survey it should have been most noticeable at the centers of Lines 2 and 1, and least likely on Line 3. As with Lines 1 and 2, no decrease is noted in the center of Line 3.

<u>GPS Surveying and Control:</u>

Location and elevation control for each gravity station was determined with a precision Differential Global Positioning System (DGPS). The DGPS system used was a ProMark

120 satellite receiver/datalogger with a tripod-mounted Ashtech 111660 external antenna. The differential aspect results from post-processing using local CORS (continuous operating receiver stations) and has the capability of sub-centimeter horizontal and vertical resolution. Unfortunately, all but one CORS were not operating during the survey period leaving the post-processed results considerably less than optimal with resolution in the multi-centimeter range but still quite usable. Once the CORS problem was recognized station occupation times were extended from 5 minutes to 10 and 15 minutes but the narrow canyon and a single CORS limited post-processing improvement of the GPS data. In addition, many of the stations have been reoccupied up to three times. The lack of multiple CORS did not render the elevation data useless, it simply prevented the highest precision and added a level of frustration.

For perspective, here are some extracts from ASTM D6430-99 *Standard Guide for Using the Gravity Method for Subsurface Investigation* (ASTM, 2005) and comments regarding their relevance to LPQ sinkhole gravity survey.

5.3.3 *Positioning* – Position control for microgravity surveys should have a relative accuracy of 1 m or better. The possible gravity error for horizontal north-south (latitude) position is about 1 µgal/m at mid-latitudes. Positioning can be obtained by tape measure and compass, conventional land survey techniques, or a differential global position system (DGPS).

In spite of the difficulties with the DGPS data the *positioning* accuracy for the LPQ sinkhole gravity survey was well within ASTM recommendations. However, as the subsequent ASTM paragraph indicates, DGPS is apparently not regarded as a sufficiently precise *leveling* method. The present survey results might bear this out but for reasons other than instrumental accuracy.

5.3.4 *Elevations* – Accurate relative elevation measurements are critical for a microgravity survey. A nominal gravity error of 1 µgal can result from an elevation change of 3 mm. Therefore, elevation control for a microgravity survey requires a relative elevation accuracy of about 3 mm. Elevations are generally determined relative to an arbitrary reference on site but can also be tied to an elevation benchmark. Elevations are obtained by careful optical leveling or by automatic digital levels.

Figure 6 shows the topographic profile of the full length of Line 1 plotted against inter-station distance. Station interval in the central portion of the line is 10 feet and beyond the central 200 feet in both directions the station intervals were 50 feet. The circles along the profile depict station locations and elevations. Also, as indicated in Figure 6, the maximum topographic relief occurred at the extreme ends of Line 1. The highest elevation was 3401.5 feet (ASL) to the north and the lowest, 3385.8 feet to the south for a total difference of 15.7 feet.

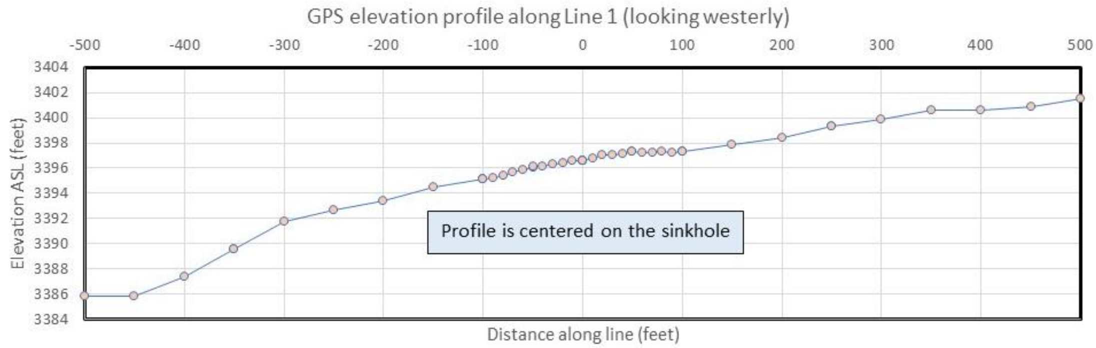

Figure 6 Elevation profile of the full length of Line 1.

Nearly half the difference in elevation along Line 1 occurs in the southernmost five stations (250 feet) where a difference of 6.9 feet occurs. The remainder of Line 1 constitutes a nearly linear gradient within which the target area next to the sinkhole occurs. The elevation profile is essentially an inverse representation of the Figure 2 observed gravity profile, as might be expected. The central portion of the line straddling the projection of the sinkhole shows no evident change in elevation that might be related to the sinkhole, as might be expected.

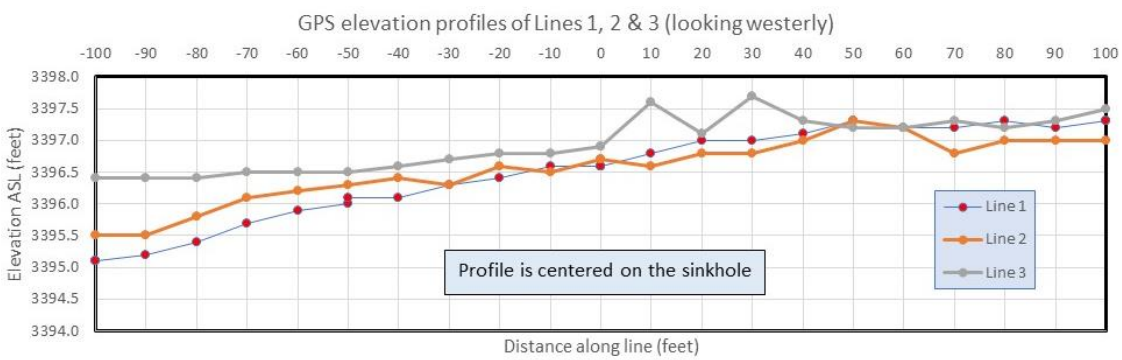

Figure 7 GPS elevations of the three lines stacked for comparison. The lack of closer correspondence illustrates the lack of precision discussed in the text.

Figure 7 is a single plot of the GPS elevations for the 3 lines adjacent to the sinkhole and shows the unfortunate lack of consistency in elevation between the lines (at points only 10 feet apart) in the GPS data. The two errant points on Line 3 at stations 10 and 30 north are certainly questionable data, but, when combined with the very slightly lower observed gravity data at those points, the resultant processed gravity barely reflects, what seems at this scale, significant differences.

The divergence on the southern end between the lines shows yet more data of questionable quality. All three lines are in the wash bottom and the location of any one line doesn't necessarily correspond with the thalweg of the drainage, so, *some* variation is to be expected from one side of the wash to the other. Lines 2 and 3 are close to the west and east sides of the wash bottom and care was taken to occasionally adjust their physical location (i.e. move slightly closer to Line 1) to keep them in the wash. Within the area covered by the central portion of Line 1 and Lines 2 and 3 there was primarily sand with several minor zones of pebbles and cobbles.

The main concern over the poor quality GPS data is that in subsequent processing of gravity data the elevations play an important role and can strongly influence the final results. Such influence generally shows up as noise and can easily be identified by referring to the unprocessed observed-gravity profiles which have no processing artifacts. The saving grace on this survey is that the observed gravity profiles show such low relief and the GPS elevations are of sufficient accuracy that the final results are minimally impacted. Nevertheless, this discussion of GPS elevations was intended to inform and alleviate any concerns about the data.

Gravity Processing:

Gravity processing consists of the steps taken to compensate for variations in latitude, elevation, subsurface density, nearby topography, atmospheric mass, solid earth tides, and instrumental drift.

Latitudinal variation in this case is minor and constitutes a slight and very gradual increase in gravity from south to north. Latitude corrections were made using the International Gravity Standardization Net 1971 (IGSN71) formula

LAC = -978031.85*(1+0.0053024*SIN(lat)^2-0.0000059*SIN(2*lat)^2)

where LAC = latitude correction and
lat = latitude.

Elevation corrections were made using (Holom and Oldow, 2013)

FAC = (0.3087691–0.0004398*SIN(lat)^2)*elev-0.000000072125*elev^2

where FAC = free air correction
lat = latitude and
elev = elevation in meters.

Bouguer slab corrections compensate for the density of the material between sea level and the elevation of the observation station

BSC = -0.04185*dens*elev

where BSC = Bouguer slab correction
dens = uniform slab density standardized to 2.67 g/cc and
elev = elevation in meters.

The infinite extent Bouguer (flat) slab also requires a correction for its spherical cap character which is called the curvature correction

CC = -(0.0004462*elev-0.0000000328*elev^2+0.00000000000000127*elev^3)

where CC = curvature correction and
elev = elevation in feet.

An additional correction occasionally useful in microgravity surveys compensates for the mass of the atmosphere above the observation station (at average barometric pressure)

ATC = 0.874-0.000099*elev+0.00000000356*elev^2

where ATC = atmospheric correction and
elev = elevation in meters.

Solid earth tidal corrections were made using the Longman algorithm (Longman, 1959) which is an accepted standard in the industry.

Drift corrections consist of linear interpolation of the difference of tide-corrected raw gravity data observed at a reference point (LPQ-001 in this case) between the beginning and ending of each survey loop. Drift corrections generally consist of two components; intrinsic or long-term drift within the instrument itself and anomalous drift (i.e. unexplained drift). Anomalous drift is defined as the remaining difference in base station readings after tide and intrinsic drift effects have been removed.

Terrain corrections consist of some form of quantitatively evaluating the affects of surrounding topography. Whether nearby topography is above or below the elevation of the station, the effect tends to decrease the observed gravity value. Terrain corrections for the present survey were constrained to within one kilometer of the station since there can only be a minor change in terrain correction for the central stations on Lines 1, 2 and 3. Terrain corrections beyond a kilometer would result in a simple shift to the data.

Results:

The results of the standard data reduction process are most easily presented in profile form as with the observed gravity plots shown in Figures 2 through 5. The following figures will have ordinate values in the -70 milligal range. This range of CBA values is a result of introducing an estimated absolute gravity value for the local base station, LPQ-001 to facilitate data processing. These values, although close to regional CBA values, should not be incorporated into any regional database until a statistically defensible tie to an established absolute gravity station has been performed.

Figure 7 shows the CBA gravity profile for the full length of Line 1 calculated using a Bouguer slab density of 2.67 g/cc. What is immediately noticeable is the increased “roughness” of the profile compared to either Figure 2 (observed gravity) or Figure 6 (elevation profile). The combination of the observed gravity and the GPS elevations during the data processing steps tends to amplify small errors in either one. This doesn’t negate the utility of the final result, it just illustrates what to keep in mind when interpreting the data. A better representation of the gravity field next to the sinkhole is Figure 9 which shows the CBA gravity for the 10 foot spaced data.

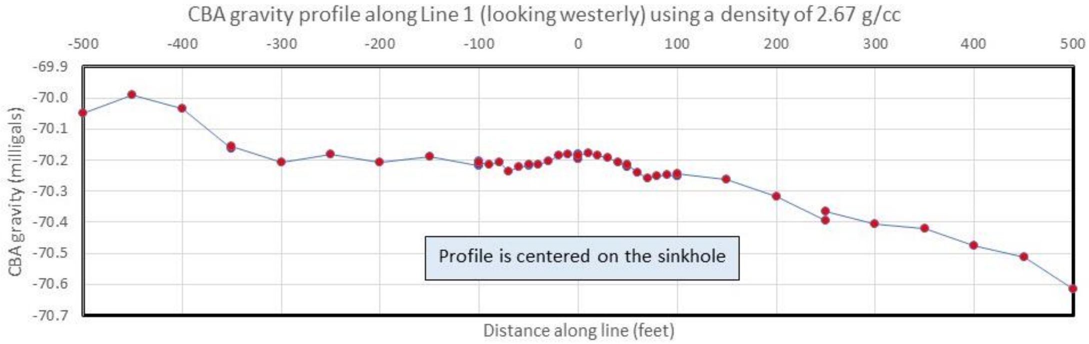

Figure 8 CBA gravity profile for the full length of Line 1 (looking westerly).

What is evident in Figure 9 (Line 1), as well as Figure 10 (Line 2) but not Figure 11 (Line 3), is a tendency for the gravity data to be slightly elevated in the vicinity of the sinkhole. In each profile is a dotted linear trend fit to the data for reference which tends to emphasize the elevated portion. It is possible that such variation in the gravity data could be a result of the shortcomings of the GPS elevation data. Alternatively, this could just as easily result from subtle changes in subsurface density, but, not necessarily related to the sinkhole. However, the relative flatness of Line 3 data tends to nullify the density change idea. In either case it is difficult to assign any significance to the feature with regard to the objectives of the survey.

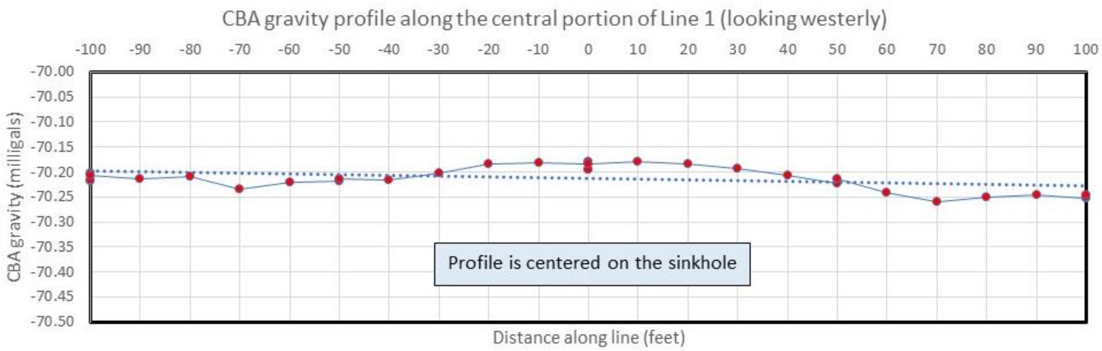

Figure 9 CBA gravity profile for the central portion of Line 1 (looking westerly). The dotted line is a linear trend fit to the data.

Figure 10 shows the CBA gravity and a similar character to that of Line 1. The half-foot, or more, deviations at the extreme ends of the line are questionable and attributed to the problem with the GPS data and post-processing.

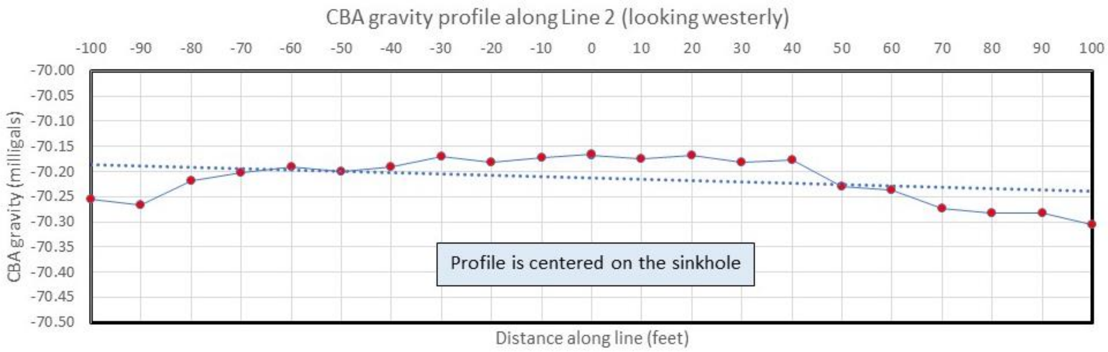

Figure 10 CBA gravity profile for Line 2 (looking westerly). The dotted line is a linear trend fit to the data.

Figure 11 shows the CBA gravity for Line 3 but does not show the same character as Lines 1 and 2. Considering that all three lines are only ten feet apart provides yet more insight to the GPS data problem. The step occurring at station 10 north on Line 3 might be worth considering as a potential indication of a structure related to the sinkhole. However, it is on the east (and opposite) side of the wash and Lines 1 and 2 are both closer to the sinkhole yet show no such step. Once again, GPS data are suspect as two of the three data points are the two errant elevations in Figure 7.

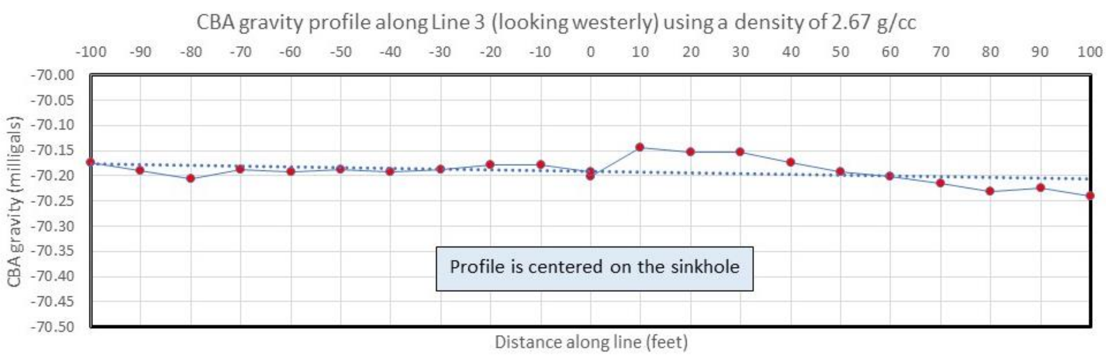

Figure 11 CBA gravity profile for Line 3 (looking westerly). The dotted line is a linear trend fit to the data.

The net result after reviewing the observed gravity profiles (which, once again, have no elevation data incorporated) and the processed CBA data all seem to indicate that there is no low density feature evident in the immediate vicinity of the sinkhole.

Conclusions:

Pursuant to the two objectives stated in the introduction, I have drawn the following conclusions based on the microgravity survey and my understanding of the local geology. These conclusions refer only to the area covered by the microgravity survey and are constrained by the resolution of the station spacing and instrumental precision, both of which, by design, are adequate for the potential target of concern.

1. I see no confirmatory evidence in the microgravity data that could be interpreted as a void of sufficient size *beneath* LPQ wash to pose a risk to vehicular traffic.

2. Geophysical mapping beyond the area of coverage may yet indicate subsurface void/s of interest or concern. Such coverage might be with electrical resistivity, as has already been done during this phase, or additional microgravity (although with the requirement of total station surveying as opposed to GPS).

3. It goes without question that a subsurface system of water transport exists as, reportedly, the sinkhole can accept and pass a considerable amount of flow from LPQ wash during intermittent floods. Neither microgravity nor electrical resistivity has the resolving power to detect, let alone map, deep voids. Such voids, assuming they exist, are highly unlikely to pose any kind of threat to vehicular traffic.

4. However, LPQ wash, although not formally mapped as such, occurs along a fault as evidenced by contrasting lithologies directly across the wash. Such a fault may consist of rubble through which heavy flow can be maintained in the subsurface. The entrapment and subsequent loss of interstitial soil between cobbles and boulders within fault rubble will likely produce localized small sinkholes that would otherwise be undetectable. Nevertheless, this is complexly faulted karstic terrain and substantial voids will occur in the limestone.

5. More than average discussion has been on the quality of the GPS leveling data. Although disappointing, due to extenuating circumstances, I want to emphasize that the final results of the survey were not compromised.

Respectfully submitted,

emailed

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