

## **Problem and Research Objective**

Karst aquifers are susceptible to contamination because surface waters are introduced directly into the aquifer system through voids, sinkholes, and sinking streams. Once in the system, the contaminants move rapidly through a network of solution conduits that are difficult, expensive and time consuming to detect using conventional methods such as well sampling or core drilling. Moreover, these discrete sampling methods have a very high probability of missing conduits or contaminant flow paths; the drill core has to be located directly above, or in very close proximity to, the contaminant in order to locate it. Similarly, monitoring wells frequently fail to detect contaminants in karst systems because the flow is concentrated preferentially in the solution conduits. The failure to detect the pathways of contaminant movement may pose a serious health hazard to the people using the aquifer system. At the same time the physical collapse of subsurface voids may undermine surface structures, causing economic damage, insurance claims, litigation, expensive engineering remediation works and, in some cases, even loss of lives (Johnson and Quinlan, 1995; Smith, 1997; Johnson, 2001). These considerations, as well as the fact that soluble rocks (gypsum and dolomite) occur within 30 meters below ground surface (m.b.g.s.) in about 10% of the state of Oklahoma, motivated the present study.

The goal of the study therefore is to investigate the feasibility of detecting and mapping subsurface karst voids using electrical resistivity tomography and to use a combined GPS/laser range survey technique to evaluate the positional accuracy of detected voids. The advantage of the resistivity method is that it is non-invasive, rapid and inexpensive relative to a conventional well drilling program. The method also generates very fine resolution (nearly continuous) resistivity image of the subsurface in two or three dimensions.

## **Study Area and Geologic Setting**

Three cave systems, Nescatunga, Corn, and Jester; all located in the gypsum deposits of western Oklahoma, were investigated (Fig. 1). The geology of the Nescatunga area consists of Permian age soluble gypsum and red shale beds of the Blaine Formation, which is in conformable contact with the underlying Flowerpot Shale and the overlying Dog Creek Shale (Miller et al., 2003; Stanley, 2002). Four gypsum beds, two dolomites and intervening clay shales comprise the Blaine Formation at this site. Medicine Logde, the lower most gypsum layer is overlain by dolomite, followed by the Nescatunga gypsum layer, which contains the cavern system. Red shales overlie the Nescatunga gypsum and then, topping the red shales, another layer of dolomite.

Several cavern systems located in the Permian Cloud Chief Formation including Endless Cave, collectively make up the Corn Caves in Wasita County (Looney and Bozeman, 1984). In the study area the Cloud Chief Formation is approximately 300 feet thick and consists of (oldest to youngest) Weatherford Dolomite, unnamed shale, a gypsum-anhydrite unit and capped with alternating sandstone and shale units. The type locality for the Cloud Chief Formation near Endless/Corn Cave reports the gypsum/anhydrite unit as being 100 feet thick (Fay, 1962). The Cloud Chief Formation is conformable with the underlying Rush Springs Sandstone and the overlying Doxey Shale (Miller et al., 2003).

The third cavern system studied was Jester cave in Greer County. According to Johnson (1987, p.47), Jester cave “developed mainly in a 16-foot-thick gypsum bed in the lower part of the Van Vacter member of the Blaine Formation. In this area, the Blaine consists of about 150 feet of interbedded gypsum, dolomite, and red bed shale.” The total thickness of the Van Vacter member in the Jester cave area is 80 feet. Six principal gypsum beds, numbered sequentially from 1 through 6, make up the Van Vacter member. A thin dolomite underlies each gypsum layer and, in most places, thin, unnamed shale overlies each of the gypsums.

## **Methodology**

The single channel Sting R1-IP-Swift<sup>TM</sup> resistivity meter with programmable electrodes was utilized for this study. Advanced Geosciences Inc. in Austin, Texas, produces the system. The idea is to pass a current of known voltage into the subsurface to be imaged through two current electrodes, and then using a second pair of potential electrodes, measure the potential drop induced by the differential response of earth materials to the penetrating current. The method is effective for detecting voids because air-filled voids show up as anomalously high resistivity regions on the resistivity field since air has infinite resistivity. On the other hand, water-filled voids show up as anomalously low conductivity spots owing to the high conductivity of water. To carry out a survey, a CREATOR<sup>®</sup> software is first used to program the desired sequence of electrode switching, corresponding to the array type chosen. Four array types, Wenner, Wenner-Schlumberger, dipole-dipole and pole-dipole, were investigated. These array types probe the subsurface in different ways even though they utilize stakes in the same position. For example, the Wenner array takes measurements along several parallel profiles at fixed depths below the ground surface (e.g. 2 m, 4 m, 6 m). In contrast, the dipole-dipole array makes a much larger density of sample measurements, which, in principle, improves the resolution of target features. Survey transects were laid out roughly perpendicular to the orientation of known cave passages and the resistivity profile of the subsurface recorded automatically according to the array type(s) specified. GPS coordinates and elevations of selected points along each transect were obtained using a Trimble ProXRS<sup>®</sup> GPS system. The raw data collected is first used to calculate apparent resistivity, which is the weighted average of the resistivity under the four electrodes. The exact formula used depends on the array type. Owing to inhomogeneities in the subsurface, the apparent resistivity is different from the true resistivity. The modeling software RES2DINV<sup>TM</sup> (Loke and Barker, 1996) was used to obtain the true resistivity from which anomalously high (low) features were interpreted against the known resistivity range of common earth materials.

Ground truth was achieved using a novel method. Internal cave morphology was first mapped in 3 dimensions using Trimble’s new 4600LS with RTK (real-time kinetic) option, part of a GPS package recently purchased by the University of Oklahoma School of Geology and Geophysics (SG&G). Our particular package permitted real-time cm-scale accuracy in both the horizontal and vertical dimensions. The ProXRS GPS system was mounted on a tripod near an entrance to the cavern system being surveyed, along with the reflectorless laser rangefinder and digital compass (Fig. 2). A DGPS carrier phase location was sited at this initial position. Differential corrections were obtained onsite using the OmniStar system and later via internet resources. A series of control points or stations were then located within the cavern itself spatially referenced to the GPS position by a series of offsets using mounted reflectors. Beginning at the entrance to the cave, the laser configuration occupied each of these control

stations successively, permitting a survey of the surrounding cavern walls (consisting of locations referenced to the control points) to be conducted. Although positioning error invariably increases with each successive control point occupied within the cavern, we achieved sub-decimeter accuracy in distance and inclination from each control point, and confirmed the accuracy by reoccupying control stations. Positioning data was then stored and analyzed using GIS (e.g. ESRI ARCVIEW) and CAD. In summary, the steps used in acquiring and utilizing the data are as follows (more details on the procedure may be found in Galen et al (2003):

1. Acquire Carrier Phase DGPS position outside cave entrance.
2. Survey a series of offset stations from this position into and through the cave using laser positioning (in filter mode) and reflectors.
3. Survey cavern wall morphology at sites of interest from surveyed offset stations with filter mode off.
4. Export positions to CAD or GIS software for visualization.

Superimposing the transect of the internal cave passage on a profile of the surface resistivity survey allowed us to determine both the position and elevation of the cave along the surface transect. Finally, the true position of the cave passage is compared to the resistivity signature of the passage to assess positional accuracy. The assessment consisted of measuring the horizontal and vertical departure of the resistivity anomaly from the true position of the cave passage.

## **Principal Findings and Significance**

### *Internal Cave Mapping*

We mapped a small portion of Endless Cave in September of 2002. Detailed map of this cave may be found in Looney and Bozeman (1984, p.39). In Figure 2, we show the traverse of the resistivity survey, the initial DGPS position outside the cave, the surveyed stations, and the data points collected to record cavern morphology, at two scales and in two and three dimensions. These are included with various sources of geographical information systems (GIS), including digital orthophoto quadrangles (DOQ's), a digital raster graph (DRG) of the USGS 7.5' Corn, Oklahoma Quadrangle, and a ten meter resolution digital elevation model (DEM), and assembled using ESRI's ARCVIEW™ software.

Figure 3a shows the location of the Endless Cave study site located on Gyp Creek near the boundary between Washita and Custer Counties. A base map of surface topography is produced by draping a 1meter DOQ over the DEM. In Figure 3b, the horizontal locations of the resistivity survey and the cave survey station transect are given by intersecting white lines. A cluster of points at this intersection denote more than 50 locations of cave wall, ceiling, and floor morphology that are used as ground truth for the surface geophysical imaging of the cavern in this locality. A three-dimensional portrayal of this data set is shown in Figure 3c, with the DOQ drape rendered transparent. This image is oriented as north-looking; north-south running section-

line roads are visible on the underlying digital raster graph going from the bottom of the image to the horizon at the middle of the image.

The internal morphology of Nescatunga caves were mapped in July, 2002. In Figure 4 we show the two- and three-dimensional GIS of a portion of Nescatunga Cave. Figure 4a shows the location of the Window study site located south of Highway 15 approximately 20 miles east of Woodward in Major Co., Oklahoma. In Figure 3b, the horizontal locations of the resistivity survey and the cave survey station transect are given by intersecting white lines connecting the survey points. A cluster of points at this intersection denote approximately 100 locations of cave wall, ceiling, and floor morphology that are used as ground truth for the surface geophysical imaging of the cavern. A three-dimensional portrayal of this data set is shown in Figure 4c, with the DOQ drape rendered transparent. The DRG beneath is the 7.5' USGS Belva, Oklahoma quadrangle. The view is nearly due east-looking.

Jester cave was mapped in June 2003. The data are still being analyzed. In any case the results generated so far demonstrate the feasibility of using the GPS laser range finder to map the internal morphology of caves. There are two downsides to this mapping procedure. First, the equipment is costly although it is rugged and reasonably mud-proof. Second, the method can only be used to map caves large enough to be entered by humans. On the positive side, the method offers a fast, accurate, and relatively non-intrusive means to map cave position and morphology. It provides “(under)ground truth” for geophysical methods used for cavern detection.

### **Significance and Contribution of the Internal Cave Mapping**

One potential application of our results is that millimeter-to-cm-scale accuracy achieved with this mapping approach could be used to ascertain the degree to which such cavern systems evolve over time scales of decades.

The following poster based on the results was presented at the annual meeting of the Geological Society of America.

Galen, M., T. Dewers, and A. Tarhule (2002). Laser positioning and 3-d mapping of Western Oklahoma karst. Poster Presented at the Annual meeting of the Geological Society of America, Denver, October 26-30.

Subsequently, the result was elaborated and a the following paper has been accepted for publication in Circular 109 of the Oklahoma Geological Survey Bulletin.Association

Miller, Galen, T. Dewers, and A. Tarhule (accepted). Laser Positioning and 3-Dimensional Digital Mapping of Gypsum Karst, Western Oklahoma, USA. Oklahoma Geological Survey.

Additional data presently being generated will be incorporated and another paper submitted for publication possibly in *Cave and Karst Science* or in the *Journal of Applied Geophysics*.

Following the poster presentation at the GSA, we have received inquiries from the USGS office in Florida about how to use the same approach to map the caves in Florida. A second inquiry

came from a Petroleum Geochemist in Ireland who also wanted to know how to use the approach to map their chemical plant. These inquiries testify to the success of our research and the dissemination outreach we have achieved.

### *Resistivity Tomography*

*ERT:* Figure 5a shows the resistivity cross-section near the highway. The plot is based on a dipole-dipole array utilizing 7 m electrode spacing. Electrode 14 was located next to an ODOT drill hole (95 m from start of survey transect, labeled C by the ODOT drill team). The depth to the bottom of the cave (measured in the drill hole) is 21 m. The cavern is approximately 5 m high by 10 m wide. This information is used to locate the cave on the resistivity profile. The cave coincides in position with an area of anomalously high resistivity ( $> 22\,000$  Ohm m), providing definitive proof of this anomaly as a void. However, the resistivity anomaly is slightly offset to the right of the true position of the cave. An examination of the measured resistivity data points revealed two missing measurements at this depth. Missing measurements occur during surveys either due to a faulty electrode or an inability of the Sting to obtain useable data at that measurement point. Hence, interpolation over the missing points could have resulted in a shift of the anomaly. Even so, the result is consistent with other investigators (see [www.agiusa.com/stingcave.shtml](http://www.agiusa.com/stingcave.shtml)) that have also reported marginal positional offsets in the true location of caves detected from resistivity profiles. No other resistivity anomalies are detected on this profile.

Figure 5b is a plot of the resistivity cross section near the window entrance. The survey utilized a Wenner array with 5 m electrode spacing (equipment failure precluded the use of a dipole-dipole array at this site). The plot revealed two anomalies, one in the center of the plot with resistivity  $> 24\,000$  Ohm m and a second to the left of the profile, but at the same depth as the first anomaly, with resistivity  $> 11\,000$  Ohm m. From the results of the GPS/laser range mapping, it was established that the centroid of the cave passage is at electrode 14 (65 m) and the depth to the bottom of the cave is 10-11 m. The cave itself measured 3 m high by 12 m at this point. Superimposing this information on the resistivity profile confirmed that the anomaly in the center of image is the target cave passage. Such excellent agreement suggests strongly that the second anomaly is also most likely a cavern passage. Although not mapped, local cavers we spoke to mentioned a second cave passage parallel to the main one we surveyed and in the general location of the anomaly identified.

These results suggest that ERT is a viable method for detecting subsurface features in the gypsum karst of Oklahoma. Major findings from the studies described above can be summarized as follows:

1. The dipole-dipole array produces high-resolution resistivity profiles that are good for imaging cavities. However, the method is prone to “current decay” with a concomitant loss of measurement points. This array type appears to be useful for relatively shallow voids but it is not possible (nor perhaps even desirable) to determine the maximum depth for which dipole-dipole is ideal because of the influence of other factors such as geology and the resistivity contrast between the target feature and the host medium.

2. The Wenner and Wenner-Schlumberger arrays appear to give rather coarse (poorly resolved) resistivity signal of the target voids. For example, void signatures in the resistivity profile typically extended over 2-3 times the actual size of the cavity. As a result, the likelihood of missing a void is high if one were to drill to the target cave or feature based on the image detected with these arrays. Finally, the depth penetration of these arrays is also more limited than the other methods used.
3. The pole-dipole array yielded the best results in terms of depth penetration, detection consistency and image resolution. We have, therefore, adopted and recommend this array type for detecting cavities in the gypsum karst of Western Oklahoma. The downside to this method is that the “infinity” electrode has to be separated from the survey transect by about 5-8 times the length of the survey transect. In closed quarters or small plots this requirement can be a challenge to meet as it increases the number of landowners from whom one has to request permission.

Based on the experience and confidence gained from the above studies, we proceeded to map one passage in the Jester Cave system that is too small to be entered by humans. The data, however, are still being analyzed. We have also carried out a 3-D resistivity survey of a part of the Nescatunga cave system and the data are still being analyzed.

In terms of dissemination, the results of resistivity tomography generated to date have been presented at the Annual Meeting of the Geological Society of America:

Tarhule, A., T. Halihan, T. Dewers, R. Young, A. Witten (2002). Integrated subsurface imaging techniques for detecting cavities in Oklahoma evaporite karst. Annual meeting of the Geological Society of America, Denver, October 26-30.

A paper has also been accepted for publication in circular 109 of the Oklahoma Geological Survey Bulletin.

Tarhule, A., T. Halihan, T. Dewers, R. Young, A. Witten (accepted) Integrated Subsurface Imaging Techniques for Detecting Cavities in the Gypsum Karst of Oklahoma. Oklahoma Geological Survey.

The results achieved to date are encouraging and have satisfied several cardinal objectives of the study. Even so, it is becoming increasingly clear that some of the original objectives will not be met. These include the following:

- a. It may not be possible to establish definitively the smallest size of cavity that can be detected with resistivity tomography. The reason is that detectability depends is a function of the interactions of several factors, which defer from one site to another. Proposing a numerical value even based on successful empirical findings at one or a few sites may therefore neither justified nor helpful.
- b. We have also not found suitable site for testing the feasibility of detecting vertically stacked voids.

- c. Finally, we have not evaluated the effect of conduit geometry in amplifying or moderating the resistivity signal. In our experience to date this objective probably is not justified by the resolution achievable with resistivity tomography.

Clearly, therefore, the approach has several strengths but some drawbacks. The best possible use of our results therefore is to complement traditional aquifer characterization and monitoring techniques. For example, resistivity tomography would be especially useful and cost effective for determining suitable locations for drilling monitoring wells in karst aquifers.

## **Conclusions**

This study described an innovative approach for mapping caverns in gypsum karst with resistivity tomography and then using a three-dimensional digital mapping of the caverns to ground truth the anomalies detected. The approach is much more rapid and cost effective than the traditional approach of drilling to confirm target features. Insights gained from the study are useful for investigating buried karstic features for which prior ground truth is not feasible. The study demonstrated the feasibility of detecting cave passages with resistivity tomography and identified the most effective array type for the gypsum karst of Western Oklahoma. The results of the 3-D mapping of internal cave morphologies have begun to attract attention within the cave mapping community as reflected in the requests we have received so far. Analysis of data already collected to map cave passages that are too small for humans, as well as three-dimensional resistivity mapping are continuing.

## **Acknowledgement**

We acknowledge with gratitude financial support provided by the Oklahoma Water Resources Research Institute (OWRRI), which provided funding for the resistivity equipment. Additional support by Oklahoma Department of Environmental Quality (ODEQ) Oklahoma allowed us to involve several graduate and undergraduate students in the research. The Oklahoma Transportation Center (OTC), also provided funding that enabled us to investigate the different though related aspect of karst geohazards. We thank especially Drs. Gorman Gilbert and Thomas Landers (OTC) and Donald Barrett (ODEQ) for coordinating the research initiatives. We acknowledge with gratitude the assistance and cooperation received from the landowners including Gary and Cinda Innman, Mr. Richard Harris, and Mr. L. Harms. Sue and John Bozeman introduced us to these caves and the owners and provided valuable background information. We thank Scott Chistenson (USGS), Curt Hayes (Consulting Geologist for ODOT) and Jim Nevels (Chief soil scientist, Materials Division at ODOT) for their cooperation and assistance on various aspects. We are grateful to Gaylen Miller for field assistance and support provided by the Oklahoma Geological Survey. Finally, we are pleased to acknowledge the contribution of our field assistants (Mark Jaeger, Zakari Saley-Bana, Julie Turrentine, Brent Wilson, and Joseph Zume).

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## FIGURES

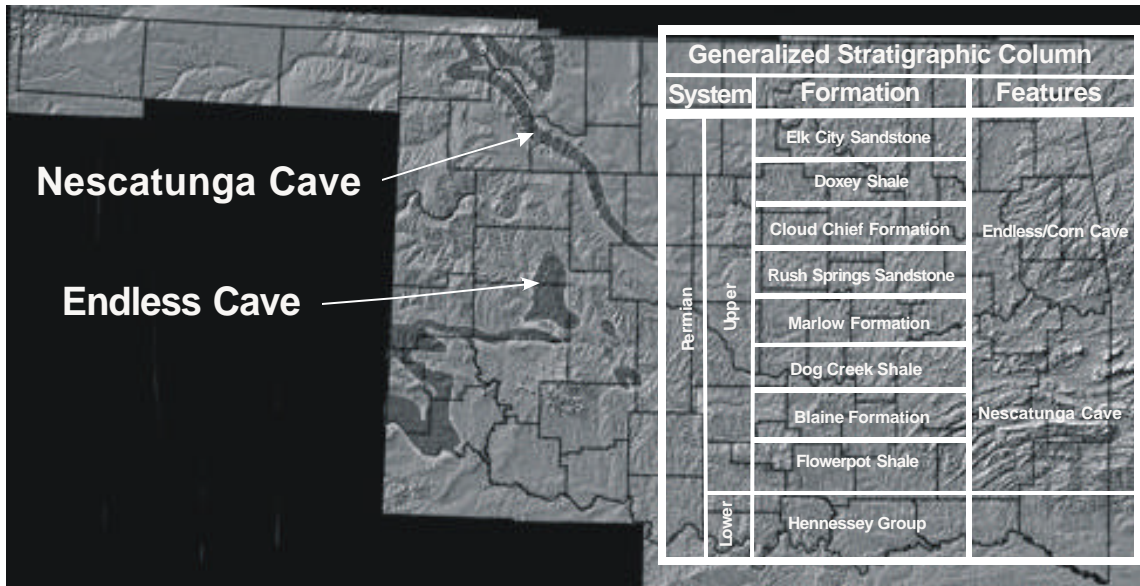


Figure 1

Figure 1. Locations of the study areas on the Oklahoma state digital elevation model, and a generalized stratigraphic section of the gypsum members housing the surveyed caves. The grey shaded regions outline regions of Oklahoma underlain by gypsum and susceptible to karst-related collapse and other hazards (after Johnson and Quinlan, 1995).



Figure 2a



Figure 2b

Figure 2A. A co-author (GM) showing the digital mapping method in action, taking a laser position of horizontal distance, vertical distance, and azimuth to a reflector shot point. The reflectorless laser rangefinder, a digital compass, and handheld computer are all mounted on a monopod/tripod assembly. Cave graffiti seen in the background unfortunately is a common occurrence close to the entrance. B. The other end of the survey: reflection of camera flash is seen from bicycle reflector used in laser positioning of cave transects.

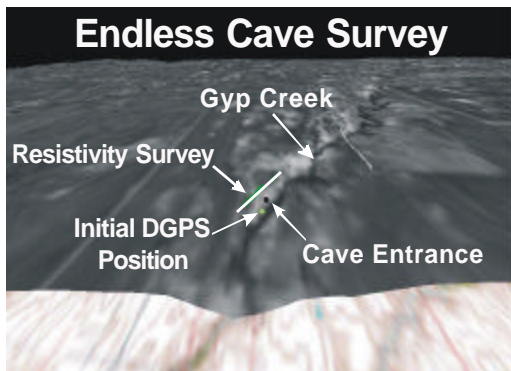


Figure 3a

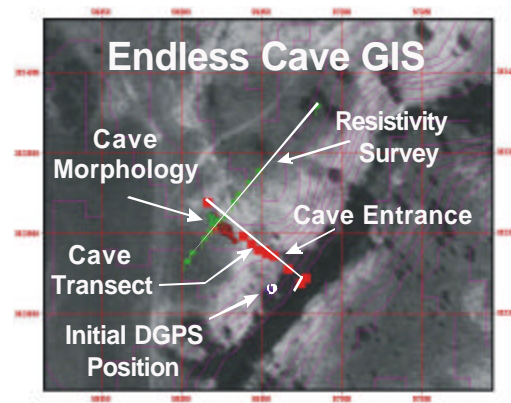


Figure 3b

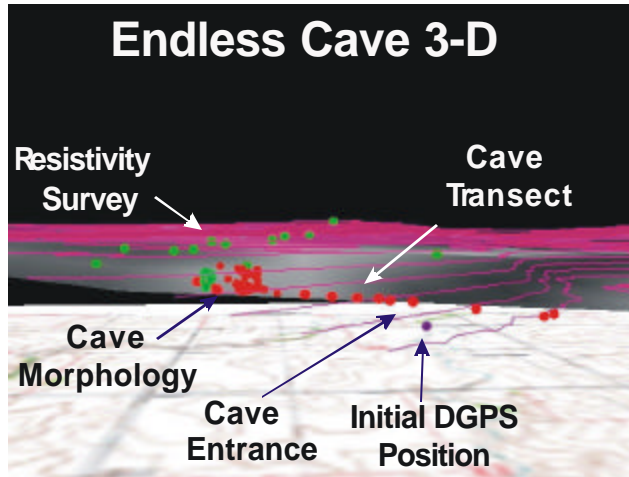


Figure 3c

Figure 3. Results of survey at Endless Cave, part of the Corn Caves in Washita Co., Oklahoma in September, 2002. A. Location of study area viewed from the south on draped DOQ/DEM. B. Two-D GIS of cave locations, cave morphology, and surface resistivity survey line discussed by Tarhule et al. (2003, this issue). C. Three-D GIS depiction of cavern location beneath ground surface. Contour interval is 2m, and UTM grid shows 50m spacing for scale.

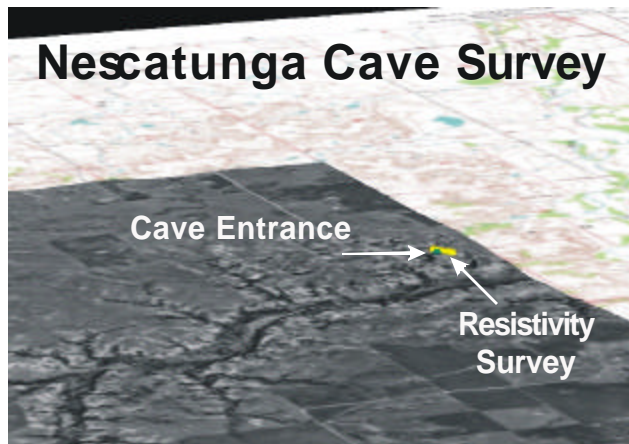


Figure 4a

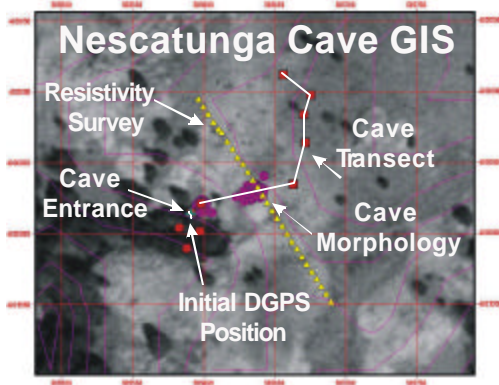


Figure 4b

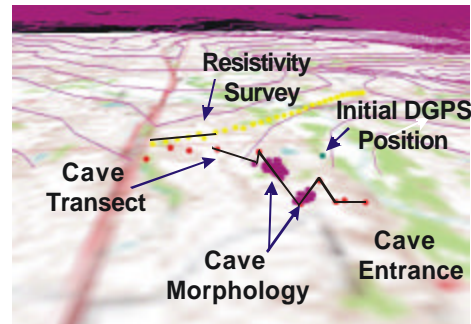


Figure 4c

Figure 4. Results of survey at the Window area, Nescatunga Caverns, in Major Co. Oklahoma, in July, 2002. A. Location of study area viewed from the southwest on draped DOQ/DEM. B. Two-D GIS of cave locations, cave morphology, and surface resistivity survey line discussed by Tarhule et al. (2003, this issue). C. Three-D GIS depiction of cavern location beneath ground surface. Contour interval is 2m, and UTM grid shows 50m spacing.

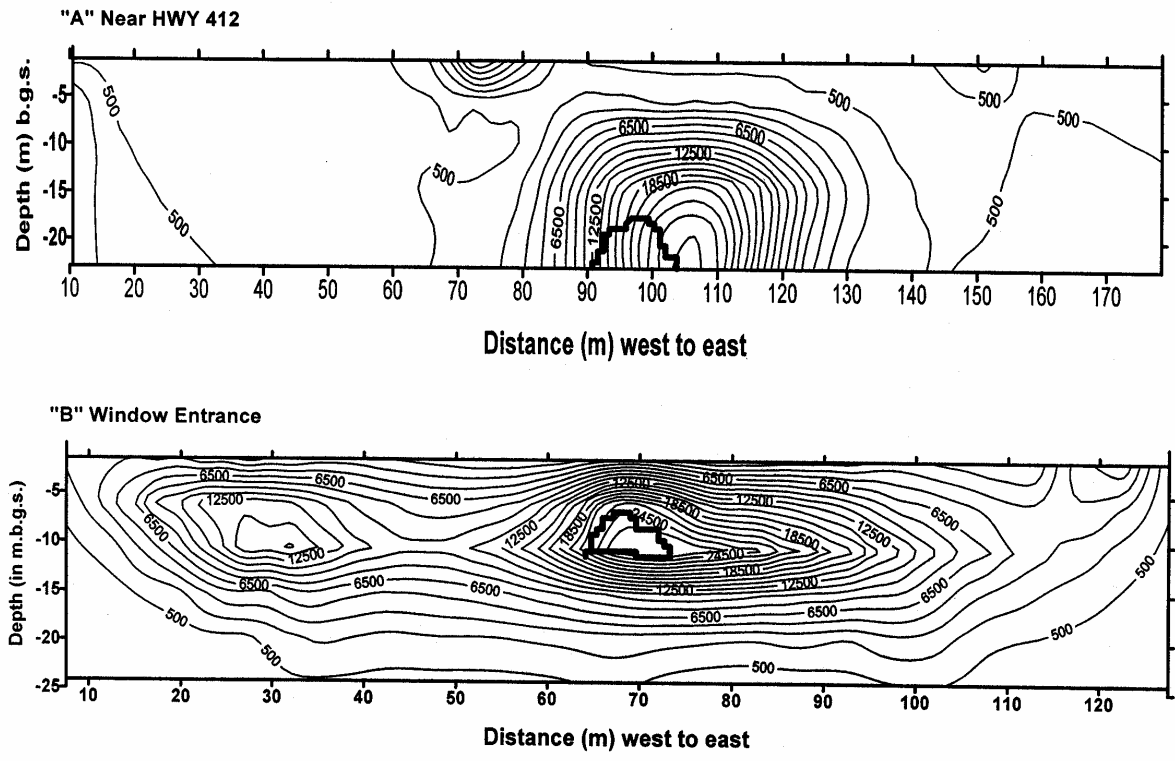


Figure 5. 2-Dimensional resistivity cross-sections of the subsurface (a) near HWY 412 based on a dipole-dipole array and 7 m electrode spacing, and (b) near the window entrance based on a Wenner array and 5 m electrode spacing. The true locations of the cavern is shown on both plots and contours represent resistivity values in Ohm m.

