Reliability of dipole-dipole electrical resistivity tomography for defining depth to bedrock in covered karst terranes

W. Zhou · B.F. Beck · J.B. Stephenson

Abstract Sinkhole collapse is one of the main limitations on the development of karst areas, especially where bedrock is covered by unconsolidated material. Studies of sinkhole formation have shown that sinkholes are likely to develop in cutter (enlarged joint) zones as a result of subterranean erosion by flowing groundwater. Because of the irregular distribution of pinnacles and cutters on the bedrock surface, uncertainties arise when "hit-or-miss" borehole drilling is used to locate potential collapse sites. A high-resolution geophysical technique capable of depicting the details of the bedrock surface is essential for guiding the drilling program. Dipole-dipole electrical resistivity tomography (ERT) was used to map the bedrock surface at a site in southern Indiana where limestone is covered by about 9 m of clayey soils. Forty-nine transects were conducted over an area of approximately 42,037 m^2. The electrode spacing was 3 m. The length of the transects varied from 81 to 249 m. The tomographs were interpreted with the aid of soil borings. The repeatability of ERT was evaluated by comparing the rock surface elevations interpreted from pairs of transects where they crossed each other. The average difference was 2.4 m, with a maximum of 10 m. The discrepancy between interpreted bedrock-surface elevations for a transect intersection may be caused by variations in the subsurface geology normal to the transect. Averaging the elevation data interpreted from different transects improved the ERT results. A bedrock surface map was generated using only the averaged elevation data at the transect junctions. The accuracy of the map was further evaluated using data from four exploratory boreholes. The average difference between interpreted and actual bedrock surface-elevations was less than 0.4 m. The map shows two large troughs in the limestone surface: one coinciding with an existing sinkhole basin, while the other is in alignment with a small topographic valley. Because sinkholes were observed at the same elevation interval in similar valleys in the vicinity, the delineated trough may have implications for future land use at the site.

Key words Karst terranes · Electrical resistivity tomography · Sinkholes · Pinnacles and cutters

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Introduction

Karst is a characteristic terrane with distinctive hydrology and landscapes arising from a combination of high rock solubility and well-developed secondary porosity. It commonly develops in carbonate rocks (limestone and dolomite) which are the focus of this paper, but it may also develop in gypsum, salt, and other soluble rocks. Karst terrane is often characterized by sinkholes, sinking streams, caves, and springs. Many carbonate areas also contain solution-enlarged joints. Also known as "cutters," these features are separated by upward-protruding limestone features known as "pinnacles," as shown in Fig. 1. Carbonate rocks contain various amounts of insoluble materials. When the soluble components are dissolved and removed by groundwater, the insoluble materials are left behind. Insoluble materials also include sedimentary gravel, sand, silt, and clay deposited with the carbonates; chert and flint formed in the deposited carbonates; and iron oxides precipitated from water and from weathering of iron minerals in the original sediments. These insoluble residues accumulate on the sides of pinnacles and the bottoms of cutters. They may eventually fill the cutters and blanket the rock surface (Fig. 1). The bedrock may also be mantled by allochthonous sediments such as volcanic ash, alluvial sediment, or marine sediment. Regardless of their origin, the sediments cover the limestone and obscure any solution-related features in the underlying bedrock.

Irregularly distributed cutters and pinnacles have significant effects on land development. When combined with other factors, cutters constitute potential areas for sink-

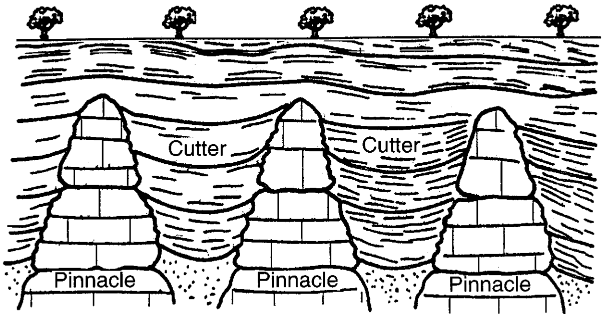

Fig. 1
Karstic cutters and pinnacles blanketed by overburden soils (modified from Sowers 1996)

hole development (Benson and others 1998), and pinnacles contribute to differential subsidence of the ground surface and building foundations. Because the elevation of the limestone/soil interface varies dramatically with location, defining the depth to bedrock with boring data is time-consuming and expensive and may be misleading because of inadequate data density. However, in contrast to other residual soils produced by the mechanical and chemical breakdown of rock from the ground surface downward, the boundary between rock and soil is often relatively sharp (Sowers 1996). Whether residual or transported in origin, the overburden soil has different properties than the underlying carbonate rock. The contrast provides the basis for applying geophysical techniques to depict the bedrock surface in covered karst terranes.

Electrical resistivity tomography

The electrical resistivity method has been used in geotechnical and environmental investigations for about a century. It may be the most frequently used for site investigation in karst areas (Franklin and others 1981), especially when the overburden soil is clay-dominated (Cook and Nostrand 1954). The electrical conductivity of clayey soil and carbonate rock has an electrolytic origin, whereas most earth materials do not conduct electricity very well. According to Archie's law (LaMoreaux and others 1984), electricity is conducted through interstitial water by ionic transport. Carbonate rock in general has a significantly higher resistivity than clayey soil because it has much smaller primary porosity and fewer interconnected pore spaces. Its typical resistivity value is more than 1000 ohm-m (ohm-meters; Telford and others 1990). Clayey materials tend to hold more moisture and have a higher concentration of ion to conduct electricity, therefore, have resistivity values less than 100 ohm-m (Telford and others 1990). The high contrast in resistivity values between carbonate rock and clayey soil favors the use of resistivity method to delineate the boundary between bedrock and overburden.

For the traditional resistivity method, four metal stakes or electrodes are driven about 0.3 m into the ground. One pair of electrodes is used to introduce direct-current electricity into the subsurface and the second pair of electrodes is used to measure the potential (voltage) difference in the earth. After a data point is obtained, the electrodes are moved to gain data at different locations at the same depth (electric profiling) or at different depths at the same location (electric sounding). The resistance of the ground circuit is calculated by Ohm's law: Resistance = Voltage/Current. The resistivity is then calculated using the electrode geometry and the resistance. However, the measured resistivity is affected by how the electrodes are placed in the ground with respect to each other – the electrode geometry. Commonly used electrode geometry includes Wenner, Schlumberger, pole-dipole, and dipole-dipole. Comparing with the other arrays, dipole-dipole provides the highest resolution and is most sensitive to vertical resistivity boundaries (Griffiths and Barker 1993) as are found at pinnacle and cutter interfaces. However, the data collected from dipole-dipole array are easily affected by near-surface resistivity variations (Griffiths and Barker 1993) and therefore can produce noisy data at sites with cultural relics.

Electrical Resistivity Tomography (ERT) is a straightforward extension of the traditional electrical resistivity method. Figure 2 shows the data collection sequence for the dipole-dipole array in an ERT investigation. The symbol "a" denotes the unit spacing of electrodes, which is selected based on the desired depth of penetration, the required resolution, and the type of array. The electrode spacing and dipole separation are constant for each traverse (*n*) and increases with each successive traverse. Larger electrode spacing provides data from greater depths, but with lower resolution. Computerized instrumentation permits automatic selection of four electrodes from a multiple-electrode array to be used for each measurement, which expedites the data collection process significantly.

The measured apparent resistivity is a volume-averaged value affected by all the geologic layers through which the induced electric current flows. An inversion program converts the array of apparent resistivity data into a model of the geology that would yield the observed distribution of apparent resistivity values. The product of

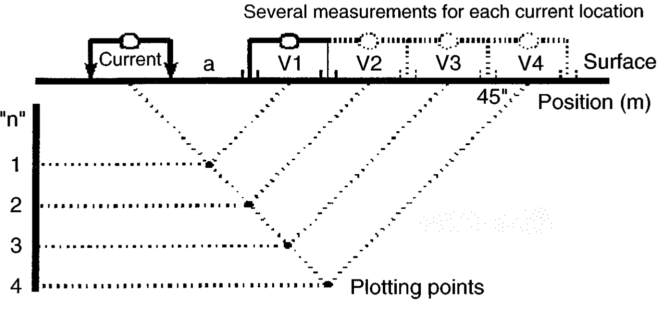

Fig. 2
ERT data measurement sequence using the dipole-dipole array

the data inversion process is a two-dimensional image (a tomograph) showing a distribution of true (modelled) resistivity values. Because a perfect reproduction is impossible, an iterative process is normally used to refine the model until the apparent resistivity distribution matches the raw data as closely as possible. No a priori information on the resistivity distribution is involved, so the resulting image is free of interpreter bias (Griffiths and Barker 1993).

The exact depth of the bedrock surface cannot be determined however from the true resistivity tomographs because even a sharply contrasting limestone/clay boundary appears transitional on the processed image. In addition, it is very difficult to determine the in-situ resistivity values of the bedrock and soil. Therefore, the position of the bedrock/overburden boundary cannot be interpreted accurately unless "ground-truth" data are available for the transect.

Field investigation

Data collection

Electrical resistivity data were collected along 49 transects over an area of approximately 42,037 m^2 (Fig. 3) using dipole-dipole ERT. The Swift/Sting electrode system (Advanced Geosciences Inc.) was used for data collection. Thirty-nine soil borings revealed approximately 9 m of unconsolidated clay underlain by karstified limestone. The depth to bedrock was defined as the depth to auger-refusal in the borings. At the site, the limestone and the land surface dip approximately 6 m/km toward the west. There are seven sinkholes (A, B, C, D, E, F, and G in Fig. 3) immediately surrounding the site. A series of springs and seeps discharge groundwater to a local stream along the base of the slope on the west and north sides. The springs appear to emerge from joints in the limestone.

The electrode spacing along each transect was 3 m. The length of the transects varied from 81 m to 249 m. Each transect included 28, 56, or 84 electrodes. The transects were arranged to correspond with a pre-existing soil boring grid, as shown in Fig. 3. On average, 220 data points were collected for each 28-electrode transect, 700 data points for each 56-electrode transect; and 1200 data points for each 84-electrode transect.

Data processing

The data were processed to generate two-dimensional resistivity models of the subsurface using RES2DINV, inversion software developed by Loke (Loke 1996; Loke and

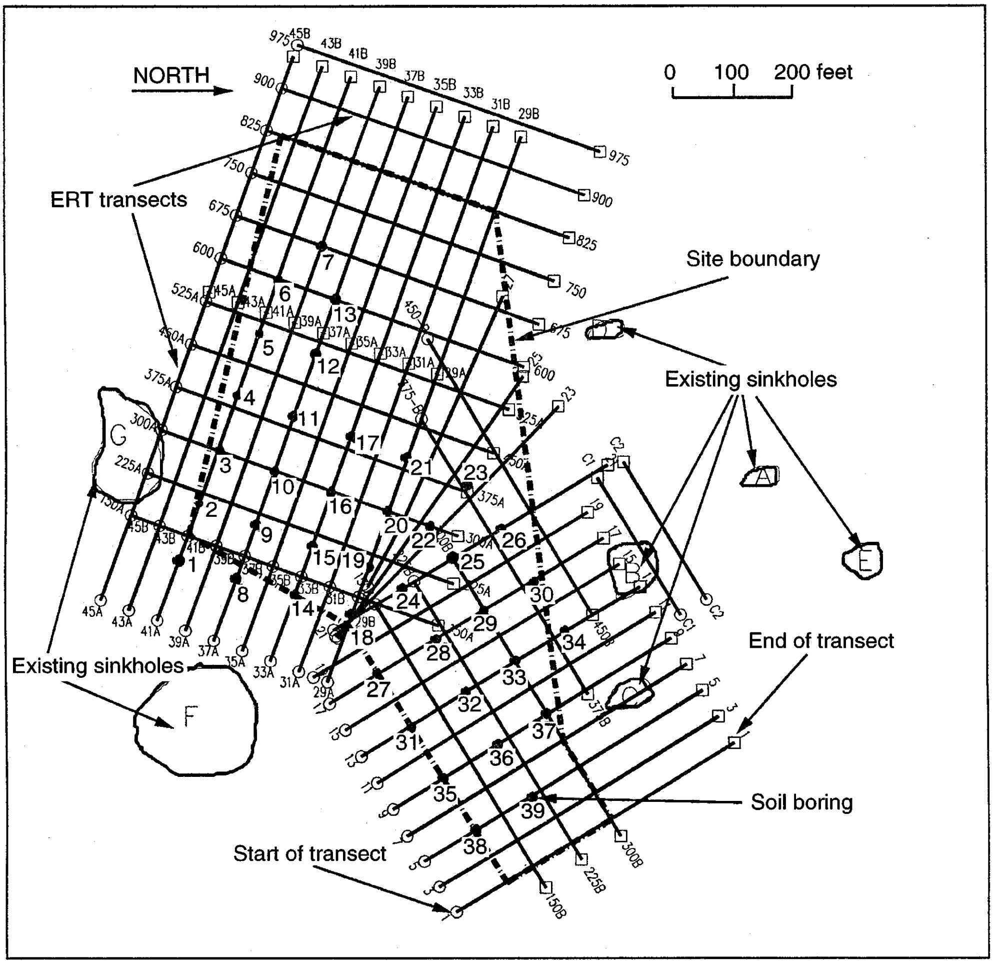

Fig. 3
Layout of ERT transects at the investigation site

Barker 1996). The Root-Mean-Square (RMS) error quantifies the difference between the measured resistivity values and those calculated from the true resistivity model. A small RMS value indicates a close match. The acceptable match is defined by the convergence limit, the default value of which is 5% change in the RMS error between iterations. Figure 4 shows the RMS error distribution for the processed transects. The average RMS error is 37.1%, with a minimum of 1.8% and a maximum of 118.2%. About 82% of the lines have RMS errors less than 50%.

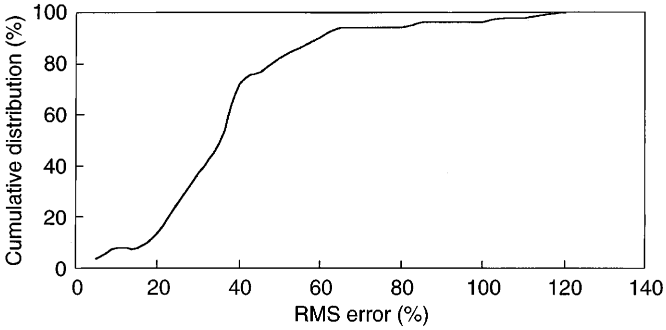

Fig. 4
RMS error distribution

Interpretation of bedrock surface elevation using borings data

Data from 36 pre-existing soil borings (Fig. 3) were used to define the limestone/clay boundary. Borings 18, 22 and 23 were not located in any transects and not used for the interpretation. However, the boring data were spatially more localized than the apparent resistivity data. Incorporation of the boring data into the true resistivity profile is not straightforward. Figure 5 shows boring data on the tomograph of transect 41A. The depth to bedrock does not correspond to a single value of resistivity. Therefore, two assumptions were made to facilitate the interpretation: (1) The contact between bedrock and soil is laterally continuous and corresponds to a single value of resistivity; (2) the contact is sharp rather than gradational. Table 1 shows the elevations of the limestone surface interpreted from the tomographs and the borings. The elevation data from borings intercepted by more than one transect were used to test the repeatability of ERT at the site. The elevation difference was calculated from two transects intercepting the same boring. The error distribution is shown in Fig. 6. The elevations interpreted from different transects differ as much as 10 m. The average difference is about 2.4 m. Seventy-four percent of the data points have errors less than 3 m.

The large RMS errors and lack of agreement between perpendicular transects result from a variety of causes, including the following.

1. Data quality: The data are affected by various factors, such as wind, clouds, rain, nearby metallic materials, animals, and even solar flares. The automatic data collection system expedites data collection process, but it limits the ability to control data quality.
2. Limitations of electrical methods: the measured apparent resistivity data are average values representing a volume of geologic material. The volume-averaging inherent in resistivity methods tends to obscure small-scale irregularities in the geologic interfaces. The data are more generalized at greater depths.
3. Non-uniqueness of the modelling results: It is possible for different geological models to produce similar profiles of calculated apparent resistivity.
4. Inaccuracy in the soil boring data: the soil borings may record the top of the weathered limestone zone, rather than the top of unweathered bedrock. Some borings may have been stopped by residual chert boulders in the overburden.
5. Impact of three-dimensional geology: the two-dimensional program RES2DINV does not accurately model three-dimensional geology. For surveys conducted across the strike of elongated structures, a two-dimensional model may be reasonably accurate. However, significant variations in subsurface resistivity in a di-

Fig. 5
Example tomograph (transect 41A) showing modelling resistivity and boreholes (1, 2, 3, and 4) to the top of bedrock

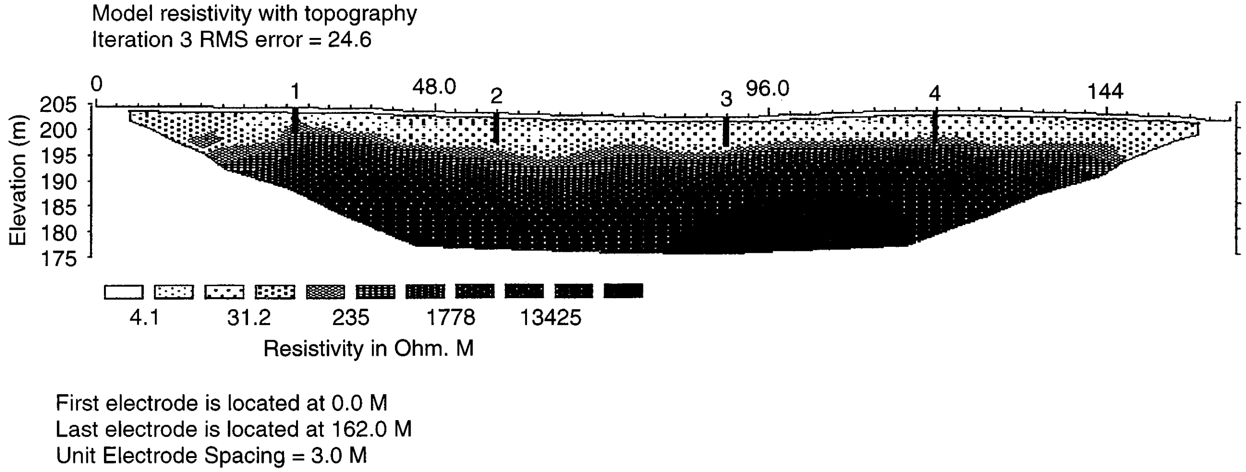

Table 1
Bedrock-surface elevations from tomographs and borings

Data from boring		Data from electrical resistivity tomography			Difference (m)
Soil boring	Elevation (m)	Transect	Elevation (m)	Average elevation (m)	
1	197.3	41A	198.2	198.2	−0.9
2	195.4	41A	193.9	194.7	0.8
		41B	195.4		
3	193.0	41A	193.3	192.2	1.0
		41B	193.6		
		300A	189.6		
4	194.5	41A	195.1	194.4	0.2
		41B	193.6		
5	194.5	41B	193.3	193.3	1.2
6	194.5	41B	193.9	194.2	0.3
		600	194.5		
7	197.3	37A	198.2	198.2	−0.9
8	197.0	37A	195.1	195.1	1.8
9	194.8	37A	193.6	194.1	0.7
		37B	194.5		
		300A	194.2		
10	194.8	37A	195.1	195.4	−0.3
		37B	195.7		
11	194.5	37B	195.7	195.7	−1.2
12	193.9	37B	194.8	194.4	−0.5
		600	193.9		
13	201.8	33A	201.8	201.8	0.0
14	199.1	33A	193.3	193.3	5.8
15	196.0	33A	195.4	194.9	1.1
		33B	193.6		
		300A	195.7		
16	199.4	33A	197.0	195.4	4.0
		33B	193.9		
17	195.4	29A	196.3	195.6	−0.2
		21	194.8		
18	195.1	29A	196.6	195.6	−0.5
		29B	194.5		
19	199.4	29A	190.5	193.6	5.8
		29B	191.5		
		300A	198.8		
20	198.2	29A	191.5	196.3	3.0
		29B	201.2		
21	197.0	21	193.9	193.9	3.0
22	197.6	21	197.0	197.0	0.6
23	204.3	21	205.2	205.2	−0.9
24	198.8	17	205.2	205.2	−6.4
25	194.8	17	195.4	194.8	−0.6
26	193.3	17	191.5	192.4	0.9
		300B	193.3		
27	192.4	17	196.0	196.0	−3.7
28	198.5	13	198.5	198.5	0.0
29	194.8	13	188.1	188.1	6.7
30	196.6	13	197.6	199.8	−3.1
		300B	202.0		
31	194.8	13	195.7	195.7	−0.9
32	200.0	9	202.7	202.7	−2.7
33	196.6	9	198.2	198.2	−1.5
34	195.1	9	195.4	195.7	−0.6
		300B	196.0		
35	199.7	5	200.3	200.3	−0.6
36	200.0	5	198.8	198.8	1.2

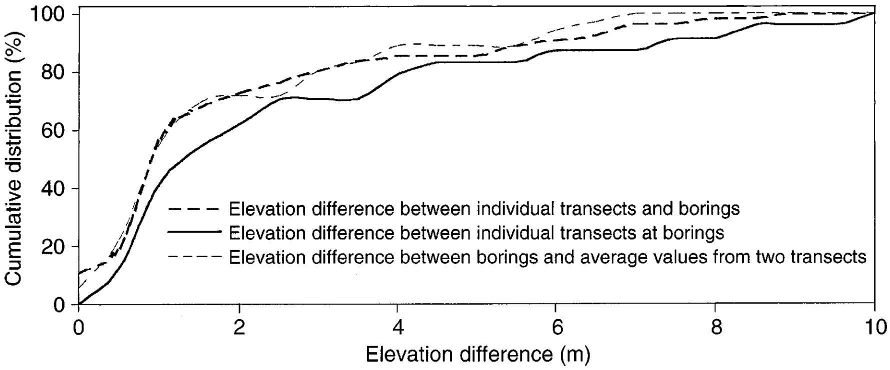

Fig. 6
Repeatability evaluation of ERT at the investigation site

rection perpendicular to the survey can cause distortions in the lower sections of the model. This effect is most pronounced when the survey line lies near a localized feature with different electrical properties than the surrounding material. Some of the bedrock-surface features (cutters/pinnacles) shown on individual transects may be caused by features that are actually laterally offset from the transect.

6. Complex geology in karst terranes: Due to the structural complexities within the residual material and the bedrock, inappropriate interpretation of the tomograph may give misleading results. Isolated, near-surface areas of high resistivity may be caused by concentrations of residual chert, iron oxide nodules, or limestone fragments. An apparent depression in the tomograph may be caused by the presence of a clay- or water-filled fracture or cavity. An apparent pinnacle in the modelled resistivity layers may be caused by the presence of a small air-filled cavity.

Averaging data at transect junctions

Some of the factors listed above are inevitable when applying resistivity methods, but the adverse effect of the others can be reduced by an appropriately designed investigation and proper data analyses. A feature off the line of one transect can be crossed by other transects in various directions. An effective way to increase the representativeness of the interpretation is to average the elevations interpreted from intersecting transects with different orientations. If similar elevations are obtained from more than one transect, the site geology tends to be uniform and their average value may be considered more reliable. About 80% of the data points have errors less than 3 m when comparing interpretations from individual transects with the boring data. More than 86% of the data points have errors less than 3 m when the average value from intersecting transects is used (Fig. 6).

The averaging approach was further tested by calculating average bedrock elevations at all transect junctions. A bedrock-surface contour map was generated using the average values (Fig. 7). A 3-m (Fig. 7) contour interval was used because most (86%) of the interpreted elevations appear to be accurate within 3 m, as explained above. Figure 7 indicates that the limestone dips generally westward, which is consistent with the regional trend in the area. Four boreholes (BH-1 through BH-4 in Fig. 7) were drilled to evaluate the accuracy of the map. The elevation differences range from 0.2 to 0.6 m, with an average of 0.4 m (Table 2). Figure 7 appears to give a good approximation of the morphology of bedrock surface.

Two ”troughs“ in the bedrock-surface are revealed in Fig. 7. Trough I coincides with a sinkhole basin (Sinkhole C). Trough II is generally in alignment with a small valley in the land surface. Because sinkholes exist at approximately the same elevation within valleys elsewhere around the site, this anomaly could indicate the presence of a zone of potential sinkhole development. Additional geologic drilling is required to confirm this interpretation.

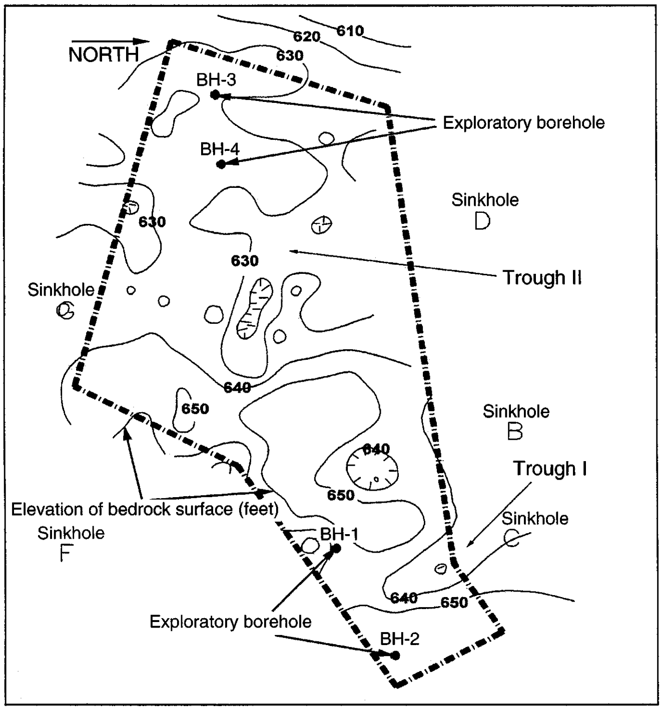

Fig. 7
Bedrock surface generated from data at transect junctions (Sinkholes A and E are off the map)

Table 2
Bedrock-surface elevations reduced from Fig. 7 and those obtained from exploratory boreholes

Exploratory boreholes		Elevation from Fig. 7 (m)	Difference (m)
	Elevation (m)		
BH-1	196.0	195.4	0.6
BH-2	198.8	199.1	−0.3
BH-3	192.7	192.4	0.3
BH-4	193.4	193.3	0.2

Conclusion

ERT is a new version of traditional resistivity methodology. The limitations inherent in all resistivity methods are still applicable. The two advantages of ERT – automated data collection and imaging inversion processing – may have side effects. Automatic data collection limits control of data quality in the field. The imaging program portrays sharp geologic contacts as gradational boundaries or zones.

In karst terranes, three-dimensional variation in the geology (irregular distribution of pinnacles and cutters) can be an important factor affecting the reliability of this technique. A comparison of the depth to limestone determined from pre-existing borings with that interpreted from ERT transects showed an average difference of 2.4 m, with a maximum of 10 m. Averaging the interpreted elevations from several transects reduces the discrepancy. The bedrock-surface map generated with averaged data from the transect junctions appears to provide a reasonable representation of the bedrock surface, as verified by data from four exploratory boreholes.

This field example demonstrates that ERT is a useful geophysical tool for characterizing the bedrock surface in covered karst terranes. Proper design of transect layout and comprehensive data analysis are critical for achieving project objectives. Linear features in the limestone may be delineated by closely spaced parallel transects. Due to the limitations of this technique, ERT tomographs should be interpreted cautiously, even with the aid of ground-truth data. The interpretations should not be used to pinpoint localized features in the field unless the data are confirmed by several intersecting transects with different orientations.

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