Detection of karst structures using airborne EM and VLF

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SUMMARY

Through the combined use of multi-frequency helicopter electromagnetic and VLF data, it is possible to detect and delineate a wide variety of karst structures and possibly to assess their interconnectedness. Multi-frequency EM can detect karst features if some element of the structure is conductive. This conductive aspect may derive from thick, moist soils in the depression commonly associated with a doline, from conductive fluids in the cavity, or from conductive sediments in the cavity if these occupy a significant portion of it. Multiple loop configurations may also increase the likelihood of detecting karst features. Preliminary evidence indicates total field VLF measurements may be able to detect interconnected karst pathways, so long as the pathways are water or sediment filled. Neither technique can effectively detect dry, resistive air-filled cavities.

INTRODUCTION

To what extent are airborne electromagnetic measurements useful in detecting and characterizing karst? Which loop configurations are most beneficial? What types of karst features are most likely to be detected with airborne EM? We were motivated to ask these questions by data from an airborne geophysical reconnaissance survey of the 140 km2 Oak Ridge Reservation (ORR). A major objective of the airborne reconnaissance survey is to use the data to enhance our understanding of the groundwater hydrology of the ORR (Doll et al., 1993). About two-thirds of the bedrock underlying the ORR consists of carbonate units of the Knox and Chickamauga Groups, and one of these--the Knox--is the primary aquifer on the ORR (Figure 1) (Hatcher et al., 1992). The dolomites of the Knox Group are intensely karstified as indicated by numerous caves, enlarged fractures, sinkholes, vugs, pinnacles, and disappearing streams. If contaminants from chemical, biological, or radioactive wastes buried on the ORR were to enter these karst pathways, they could quickly migrate off the reservation and enter the Clinch River.

Our experience indicates that multi-frequency airborne EM using coplanar and coaxial coil orientations are effective in detecting karst features which have some conductive aspect, such as a cavity partly or completely filled with conductive sediments or fluids, or a near-surface depression filled with conductive soils. More resistive karst features are not detectable.

VLF measurements also appear to be useful in evaluating the connectedness of karst pathways. Total field VLF data from the ORR may indicate connected groundwater flow paths in karstified units. For currents to be channeled into such units, the karst features need only be connected and water-filled. The presence of conductive sediments is unnecessary. Thus, the VLF data complements the multi-frequency EM data, though neither technique is able to detect resistive, air-filled cavities.

KARST GEOLOGY OF OAK RIDGE RESERVATION

The ORR contains a wide variety of karst structures, ranging from vuggy limestones to caves. It is likely that some formations contain well-connected karst conduits. This is suggested by a linear set of dolines along the crest of Chestnut Ridge in the vicinity of the Y-12 facility (Lietzke et al., 1989), by several known caves, mostly occurring in the Knox Group, and also by various geologic and hydrologic indicators. Rounded gravel and cobble sized stones found in some cavities indicate large volumes of water have rapidly passed through some underground passages. Pressure transducers in wells intersecting cavities show rapid changes following precipitation events. A few successful tracer studies have shown karst interconnectivity. Airborne EM and VLF data also provide evidence suggesting interconnection of karst structures.

NUMERICAL MODELING OF KARST FEATURES

We used 3-D numerical models to determine what physical characteristics a karst feature would need in order to be detected with airborne EM. The computer program used to compute our models was EMIE3D (Wannamaker, 1993). This code allows for 3-D inhomogeneities in a layered earth and can compute responses for horizontal coplanar, vertical coplanar, and vertical coaxial loop configurations. Modeling indicates that even fairly large cavities may go undetected in an airborne survey unless a sizeable portion of the cavity is filled with conductive sediments or fluids. In Figure 2 we see the maximum secondary EM response as a fraction of the host response for a 4175Hz horizontal coplanar loop-loop system over an air and sediment filled 60m x 60m x 40m prismatic karst structure as the volume fraction of 10 ohm-m conductive sediments varies from 0% to 100%. Taking 10% above or below host response as the threshold level of detectibility for an anomalous body, the secondary EM response exceeds this amount when the quantity of conductive sediments in the cavity approaches 40%. The volume of conductive fluids or sediments in the karst cavity is more critical to airborne detection than the depth to the top of the karst structure. In Figure 3, we see that the secondary EM response decreases gradually with depth. A karst cavity having the same dimensions as the one in Figure 2, and three-quarters full of conductive material, has the same maximum response at 20m depth as the half full cavity had at only 5m depth.

Perhaps the most critical parameter in detecting conductive karst structures is the thickness of conductive sediment cover. In Figure 4 we see that the secondary EM response decreases below 10% of the host response before the thickness of the 10 ohm-m conductive overburden reaches 3m if the body is buried 10m deep. This figure is only slightly altered if the body is only 5m deep. Overburden over karst units on the ORR rarely reach resistivities as low as 10 ohm-m, so it is likely that we are able to detect karst features through somewhat thicker layers of overburden.

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The size of a conductive karst feature which can be detected is dependent on the depth and conductivity of the target. Based on modeling a prismatic cavity, 3/4 full of 10 ohm-m sediments, and buried 5m to the top of the cavity in a 1000 ohm-m half-space, it is reasonable to expect to detect targets possessing dimensions of 30m x 30m x 20m at a transmitter-receiver height of 30m and frequency of 4175Hz. If we reduce the transmitter-receiver height to 15m, as was possible in cleared areas during the high resolution phase of our survey, the EM response over background levels increases by a factor of about three, and we can see smaller karst features. Since our reconnaissance phase line separation averaged about 45m, we are confident that we were able to detect conductive karst features on the order of 30m x 30m x 20m.

AIRBORNE EM AND VLF DATA

In the ORR airborne data, geophysical signatures which may indicate karst are common. However, for this abstract, we shall restrict our discussion to three locations where previously unidentified karst features have been detected using reconnassiance airborne data. These locations are labeled A, B, and C on the reservation map in Figure 1. The average flight line spacing was about 50m and the average sensor height about 30-40m above ground level. Other examples will be noted in the accompanying presentation.

Location A in Figure 1 indicates a probable karst structure in the Mascot Dolomite of the Knox Group. It was identified based on the similarity of its 4175Hz coplanar and 4600Hz coaxial apparent resistivity signatures to those of a known sinkhole less than a kilometer away (Figure 5). In a subsequent inspection of the area, a small disappearing stream was located near the anomalous zone.

Location B in Figure 1 is on Freels Bend, a section of the ORR made up almost entirely of the highly karstified Copper Ridge Dolomite of the Knox Group. The EM anomaly is strongest for the 4600Hz coaxial loop configuration (Figure 6a) and the 4175Hz coplanar coil configuration. It is much less distinct in the 850Hz coplanar data, indicating a shallow structure. On the apparent resistivity map of the 46OOHz coaxial data, the anomaly appears as a linear conductive feature connecting two or more larger conductive 'bullseyes.' Subsequent field inspection showed that the bullseyes corresponds with circular depressions in a linear topographic low trending in the direction of the conductivity anomaly. Associated but not coincident with the conductivity anomaly is a VLF anomaly which trends across Freels Bend (Figure 6b). This anomaly may indicate a separate zone of interconnected karst features causing a shortcut for water flowing around Freels Bend in the Clinch River. The strike of this anomaly parallels bedrock strike which in turn controls cave trends on the ORR (Rubin and Lemiszki, 1992). Similar VLF and EM anomalies are located across Hickory Creek Bend (Figure 1).

Location C illustrates the utility of multiple frequencies and coil configurations in airborne surveys. A significant conductor is not apparent in either the 4600Hz coaxial or the 47 15Hz coplanar apparent resistivity data. However, the 850Hz coplanar coils indicate a broad conductive structure containing smaller zones of even higher conductivities (Figure 7). It is located in the Copper Ridge Dolomite. Subsequent ground inspection in the location of the anomaly revealed a broad, linear valley subdivided by large depressions--each 3-5m deep and up to 5Om in diameter.

HIGH RESOLUTION AIRBORNE EM

At the time of this writing (March 1994), we are just beginning the high resolution phase of the ORR airborne survey. In this phase, we will examine selected areas more closely using tighter line spacings (20-30m), lower measurement heights over cleared areas, and a broader, higher frequency band--six frequencies from 7000Hz to 63000Hz--than in the reconaissance phase. Some of the areas selected for high resolution follow-up are located in karst formations. Ground geophysics has also been planned for location B on Freels Bend.

CONCLUSIONS

Airborne electromagnetics is a useful tool for locating karst features provided the soil cover, if conductive, is thin, and the karst feature has some conductive aspect. Typically, a karst cavity detectable by airborne EM should contain more conductive material than air or other resistive material. Airborne EM signatures vary from conductive 'bullseyes' to linear features connecting bullseyes. To maximize detection of karst, the airborne system should possess multiple coil orientations and multiple frequencies. Though the evidence is thus far of a very preliminary nature, VLF data may contain information related to interconnection of karst conduits. We anticipate that high resolution airborne and ground geophysical follow up combined with careful geologic investigation will improve our understanding of the sources of these EM and VLF anomalies in karst units on the ORR.

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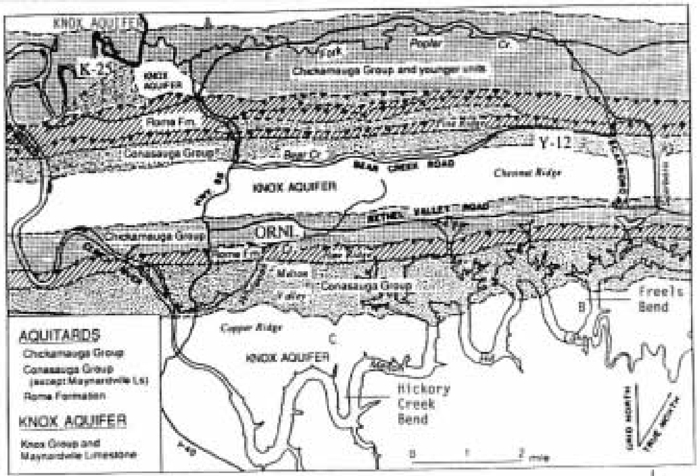

FIG. 1. Major geologic, cultural, and geomorphic features of the Oak Ridge Reservation, Oak Ridge, Tennessee, USA. Three locations where karst structures were detected by airborne EM are labeled A, B, and C. (Adapted from Solomon et al., 1992.)

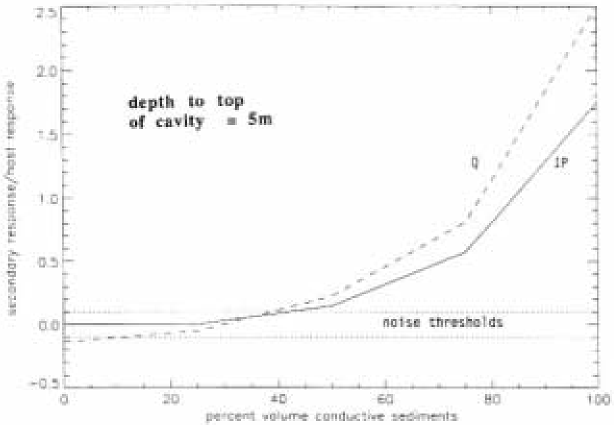

FIG. 2. The effect of conductive material in a karst cavity on EM response. The percent of 10 ohm-m conductive material (by volume) in an otherwise air-filled 60m x 60m x 40m void is plotted against the normalized in-phase (IP) and quadrature (Q) responses of a coplanar loop EM system flown at a height of 30m above ground level. The host half space resistivity is 1000 ohm-m.

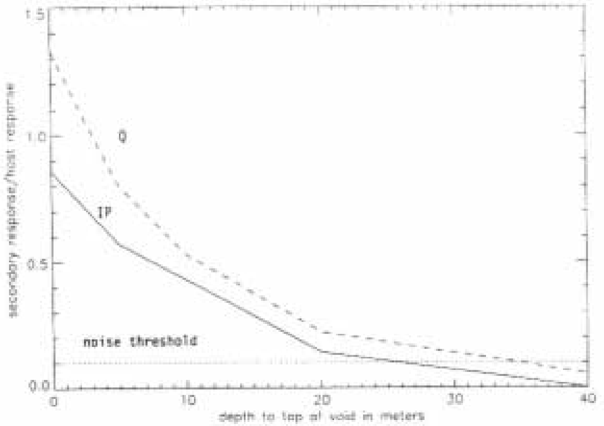

FIG. 3. Variation of the normalized in-phase (IP) and quadrature (Q) EM responses of a karst cavity with depth of burial. The karst cavity has dimensions 60m x 60m x 40m and is three-fourths filled with 10 ohm-m conductive material. Host rock resistivity is 1000 ohm-m. Flight height is 30m above ground surface.

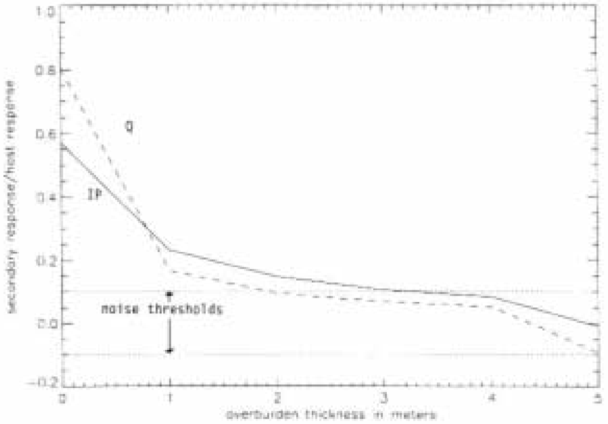

FIG. 4. The effect of conductive overburden on the normalized in-phase (IP) and quadrature (Q) EM responses of the karst model used in Figure 3 and buried to a depth of 5m to the top of the cavity.

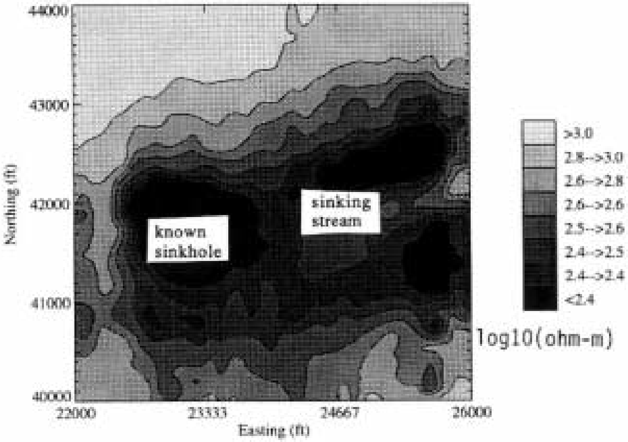

FIG. 5. Map view of 4600Hz airborne coaxial apparent resistivity over karst features marked A in Figure 1. The low resistivity zone on the left is centered over a circular topographic depression with a small cave opening located near the northern edge. The low resistivity zone in the upper right has no associated topographic depression, but a disappearing stream was located about 100m south of it.

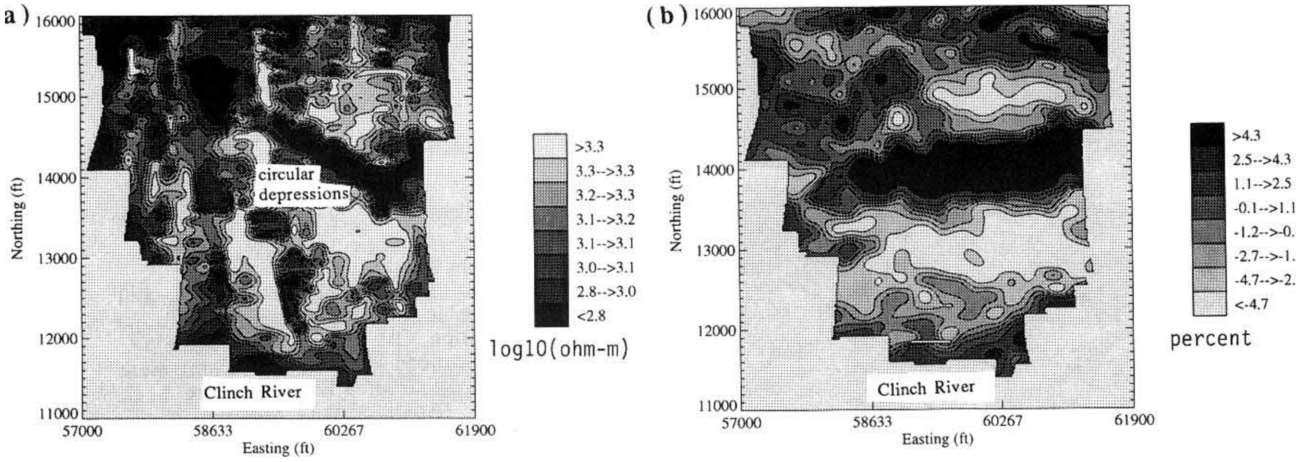

FIG. 6. Map view of (a) 4600Hz airborne coaxial apparent resistivity and (b) VLF data at Freels Bend, marked B in Figure 1. The Clinch River bounds Freels Bend. Two circular depressions lie inside a long drainage.

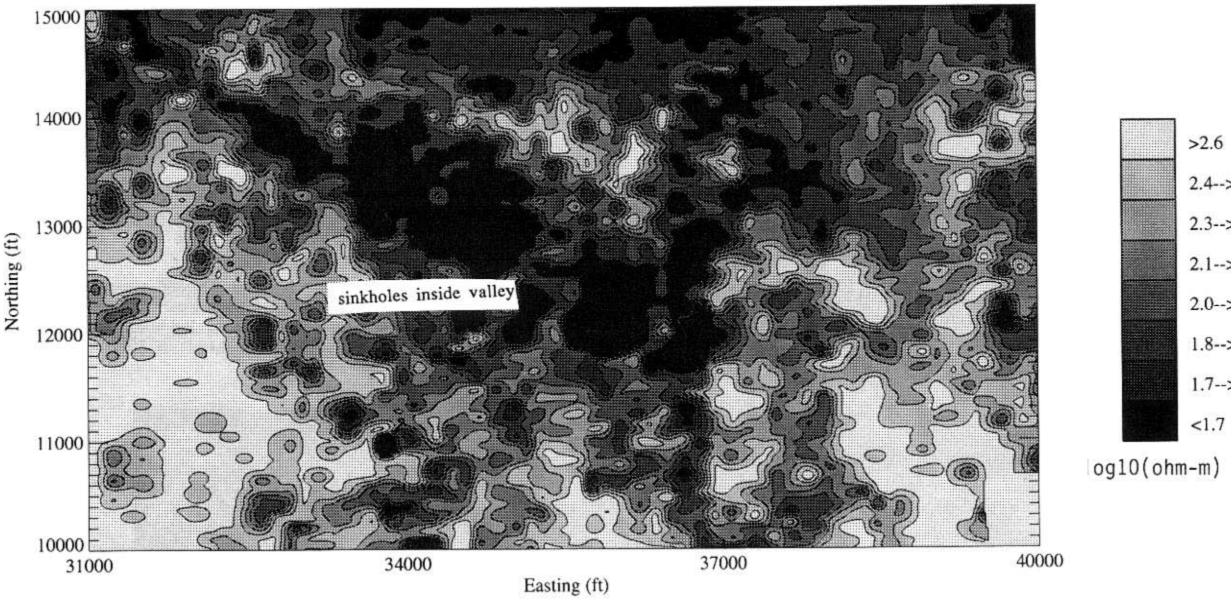

FIG. 7. Map view of 850Hz airborne coaxial apparent resistivity over karst features marked C in Figure 1. There are several obvious sinkholes along a deep valley.