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Sinkhole structure imaging in covered Karst terrain

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[1] Ground penetrating radar (GPR) and resistivity techniques have been widely used to map the locations of sinkholes in covered karst terrain. To determine whether a sinkhole is a likely preferential conduit for groundwater flow, however, requires higher-resolution imaging than that used in conventional sinkhole mapping surveys. Field observations combined with simulated surveys for a 15-m diameter 3-m deep sinkhole in west-central Florida are used to assess the resolution of GPR and resistivity surveys targeting the semiconfining unit that floors the sinkhole depression. 2D resistivity surveys clearly show the central depression as well as resistivity contrasts between the cover sediments within and outside of the sinkhole, but are inadequate for resolving breaches in the semiconfining unit or underlying conduits. A 3D GPR survey resolves vertical structure on the order of tens of centimeters within the semiconfining unit, as well as indicators of conduits that extend several meters beneath the central depression. 3D GPR thus holds promise for imaging hydrologically significant features of sinkholes. Citation: Kruse, S., M. Grasmueck, M. Weiss, and D. Viggiano (2006), Sinkhole structure imaging in covered Karst terrain, Geophys. Res. Lett., 33, L16405, doi:10.1029/2006GL026975.

1. Introduction

[2] Imaging the location and structure of sinkholes is of both academic and practical interest in covered karst terrains. Sinkholes may serve as zones of preferential recharge to aquifers and associated subsidence is a critical concern for building and road construction and maintenance. Geo-physical techniques are widely used to locate sinkholes. Detection with ground penetrating radar (GPR) is based primarily on GPR’s ability to image raveling layered sediments that fill the depressions over limestone, and to detect undulations within the clay-rich layer that often forms as a weathering product draping underlying limestone [e.g., Benson and LaFountain, 1984; Beck and Sayed, 1991; Stewart and Parker, 1992; Barr, 1993; Carpenter et al., 1998; Batayneh et al., 2002; Dobek and Upchurch, 2006]. Electrical resistivity methods are useful where there is a significant terrain conductivity difference between cover sediments and limestone or limestone weathering products [e.g., Zhou et al., 2000, 2002; McGrath et al., 2002; Roth et al., 2002; van Schoor, 2002; Ahmed and Carpenter, 2003].

[3] Sinkhole detection techniques are thus clearly well-established. For hydrogeological studies, however, it may be desirable to determine whether a sinkhole functions as a groundwater flow conduit. In west-central Florida, the clay-rich layer that blankets the limestone forms a semiconfining unit. Where this unit is breached at sinkholes, the holes function as sites of preferential recharge and can play a crucial role in determining surficial aquifer response to pumping from deeper aquifers [e.g., Stewart, 1998]. At present, resolving whether a sinkhole serves as a site of concentrated flow requires detection of groundwater motion, via pump tests, well monitoring, tracer studies, or self-potential (SP) measurements. These methods are invasive and/or require repeated site visits. It may be possible, however, to assess the probability that a given sinkhole serves as a focus of groundwater flow through direct geophysical imaging of its basal structure. More invasive tests could then focus on sinkholes with clear breaches in the semiconfining unit.

[4] El-Beihry and Hanafy [2000] report a combined GPR and resistivity survey that indicates a shallow sinkhole (1–2 m depth, ~5 m diameter) in limestone bedrock underlain by a high-resistivity anomaly fracture zone to 6–16 m depth. In contrast, Labuda and Baxter [2001] and Ahmed and Carpenter [2003] interpret low-resistivity anomalies (10–20 m wide, tens of meters deep) as fracture zones that underlie karstic recharge features. The difference in the sign of the resistivity response appears to lie in the nature of the fill—air or water—of the fractures or conduits. Nevertheless, common to each of these studies is that the fracture zones resolved from resistivity inversions are similar in lateral dimension to the overlying sinkholes or voids. Thus these resistivity surveys are not resolving individual pipes or fractures but rather zones of enhanced dissolution.

[5] GPR profiling can clearly be used to resolve meter-scale and individual karstic features [e.g., Annan, 2005]. Recently, S. Truss et al. (Imaging rainfall drainage within the Miami oolitic limestone using high-resolution time-lapse GPR, submitted to Water Resources Research, 2006), show dramatic resolution of a vertical preferential flow conduit ~4 m in diameter though time-lapse GPR imaging of moisture movement in oolitic limestone.

[6] In this paper we examine whether GPR and resistivity techniques can specifically be used to (a) resolve the structure of the clay-rich semiconfining layer that floors sinkholes in many covered karst terrains, and (b) image individual fractures or conduits below the main depression. The results of a case study on a 15-m diameter sinkhole in west central Florida are compared with field observations and simulated surveys.

2. Geologic Setting and Previous Work

[7] The study site lies within covered karst terrain in the northeastern part of Tampa, Florida, on part of the campus...
of the University of South Florida that is designated the Geopark (Figure 1). A grid of GPR surveys with 10-m spacing was run in this area by Stewart and Parker [1992], who also collected an extensive suite of cone-penetrometer tests (CPTs), and standard penetration tests (SPTs) with split-spoon sampling. Figure 2 shows one of several cross-sections assembled by Stewart and Parker [1992]. Surficial unconsolidated, clean eolian sands are underlain by silty clayey sands, silty fine sands and sandy clay units that form as a weathering by-product of underlying limestone. These latter strata together form a semiconfining unit, and constitute the top of the limestone aquifer [Stewart and Parker, 1992]. In this paper we refer to these combined units simply as the semiconfining layer. Breaches in this unit above zones of karst collapse within the limestone can localize recharge from the surficial to the underlying Florida aquifer [Stewart and Parker, 1992]. In a 100m by 100m zone that encompasses the profile of Figure 2, Stewart and Parker [1992] identify numerous depressions (at least 13) of dimensions very similar to those shown in the profile. Surface topography is relatively flat, with a maximum change of about 1 m throughout this area. The water table at the time of the study was ~1 m below land surface, as measured in a nearby well.

3. Methods

We analyze here GPR and resistivity surveys run in October 2004 over a part of a single depression, namely the depression shown in the dashed circle in Figure 2. However, because it was impossible to precisely locate the sites of Stewart and Parker’s [1992] CPTs and SPTs, the 2004 surveys presented here may image a conduit neck different from (but within meters of) the feature sketched in Figure 2. Thus we can use the deeper structure sketched in Figure 2 only as a guideline for the expected dimensions of features imaged here.

A 3D GPR survey was run over a 9.0m by 4.2m area spanning part of the 15m diameter sinkhole (gray box on Figure 1). Profiles were collected every 0.2 m with a 0.1 m along-profile sampling interval, with 200 MHz antennas and the pulse EKKO 100 system of Sensors and Software, Inc. Horizontal positions are believed to be accurate to within 2 cm. Antennas were moved incrementally over survey tapes stretched across the grid. The grassy survey surface is smooth and uniform and antenna coupling issues should not contribute significantly to amplitude variations. Elevation across the survey grid increases uniformly from south to north by about 10 cm, and was neglected in GPR data processing and interpretation. It took about 3 hours to acquire the grid. With a rotary laser-positioned system such as that recently developed and described by Grasmueck and Viggiano [2006], acquisition time could be reduced to ~10 minutes. A common midpoint (CMP) survey at the center of the grid yields a best-fitting velocity of 0.070 m/ns for the sands above the semiconfining unit. Data were dewowed,

Figure 1. Location map showing the study site and locations of geophysical surveys within the Geopark on the University of South Florida campus, Tampa, Florida.

Figure 2. Profile across two covered sinkholes compiled by Stewart and Parker [1992]. Thin vertical lines show CPTs, SPTs, or wells. The profile and locations of labeled wells and CPTs are shown in Figure 1. The dashed circle shows the larger depression that is the focus of this study. The conduit imaged with basal diffractions in Figure 5 may not correspond directly to the deeper neck sketched at 45 m on this profile, but these features lie within several meters of each other.
gained, and migrated with the Promax 3D phase shift migration [e.g., Yilmaz, 2000] using this constant velocity to focus diffractions and reposition dipping reflectors. The best-fitting constant velocity was used as the water table was not directly imaged (presumably due to the thickness of the capillary fringe), and hence there was considerable uncertainty in the velocity structure associated with the water table. Migration parameter testing and interpretation constituted the bulk of the data processing and took about two days. Migration computation time itself was only ten minutes.

[10] A synthetic GPR survey was generated using a 2D finite difference time domain code [Kruse and Jol, 2003] with 2 cm cell size and .04 ns time steps. 2D models were used because 3D representation of the desired sinkhole features exceeded the capabilities of available PCs. The 2D models simulate a line source antenna over a V-shaped trough underlain by a fracture zone, but nevertheless provide useful comparisons with real surveys.

[11] Resistivity profiles were collected with Wenner traverse geometries and a 48-electrode Campus resistivity system on the same day as the GPR survey (locations shown in Figure 1). Wenner geometries were selected because they (in theory) offer the best resolution of the depth to the high-conductivity semiconfining layer. On the eastern line (Figure 1) data were combined from two co-centered surveys, one with 0.5 m electrode spacing, the other with 1.0 m electrode spacing. A second western line was run with 0.5 m spacing to examine variability in shallow structure across the sinkhole. Topography was measured along the resistivity profiles with rod and level at 1 m intervals and incorporated in inversions run with the Res2dinv software of Geotomo, Inc [Loke and Barker, 1996].

[12] Resistivity surveys were simulated by forward modeling with the Res3Dmod program from Geotomo, Inc. followed by 2D inversions of single synthetic profiles with the same Res2dinv program used for the real data. Forward models were run with 2 model cells per electrode, 40 model cells in the direction perpendicular to the 2D surveys, and 18 layers in the vertical direction. Comparison of the forward model results with analytical solutions of simple geometries indicates that numerical errors associated with the forward model are on the order of 10% at the shallowest model depths, but decrease to a few percent or less at the depths of interest in this study (base of the sinkhole). Decreasing the size of model cells would increase numerical accuracy, but exceed the capacity of the Res3dmod program. The accuracy of the models is believed to be sufficient to address the questions posed here.

4. Results and Discussion

4.1. GPR

[13] Stewart and Parker [1992] clearly demonstrate that GPR is effective for imaging the larger-scale (10–20m) covered depressions that characterize the semiconfining unit in this landscape. The higher-density survey of this study shows that GPR can also resolve smaller, meter-scale perturbations in this horizon that may have hydrogeologic significance. Figure 3 shows migrated profiles extracted from the 3D cube that are co-located with the resistivity surveys spanning the target sinkhole. On the eastern profile, the semiconfining unit appears as a continuous exceptionally strong reflection, while on the western profile the unit is
much more irregular and weaker—two reflections appear in the central part of the profile, and the continuous reflector is lost on this particular line at the southern end of the profile. For the 3D migrated GPR data set as a whole, the semi-confining unit can be traced almost continuously across the cube (Figure 4), although manual picking was required across the lower-amplitude less coherent western portions of the grid. The lower amplitudes on the western side are not a migration artifact, and it is possible that some of these amplitude variations are a result of the non-uniform radiation patterns of the dipole antennas. Better understanding of the consequences of surveying with a single antenna polarization is a topic of future research. Time-slices through the migrated GPR cube, shown on the small insets on the left of Figure 4, demonstrate the basal tapering of the depression is remarkably conical.

Figure 4. 3D migrated GPR data cube exposing the bright reflector that corresponds to the top of the semi confining unit. Location shown on Figure 1. Red line shows location of profile of Figure 5. The deep diffraction shown in Figure 5 is offset to the northeast from the deepest part of the confining unit. Insets on left show migrated time slices at 2.35, 2.58 and 2.83 meters depth, assuming velocity = 0.070 m/ns, and demonstrate the generally conical form of the lower part of the sinkhole.

Figure 5 shows model and observed and profiles across the semiconfining unit at the location shown with the red line at the top of Figure 4. The synthetic model was designed by trial and error, based on observed velocities, to approximately match the behavior of the field data. The diffractions associated with the semiconfining unit reflection (an example is marked with 2 on the unmigrated section Figure 5c) indicate this surface is locally rough. For comparison, the synthetic model shows a vertical step of 30 cm that results in a diffraction offset 8 ns downward in time, clearly greater than observed diffraction shifts. Based on this reasoning, roughness must be on the order of 10–20 cm. Some of this roughness is captured in the migrated image (Figure 5d). We note that the upper rim of a conduit such as that simulated at the point labeled 1 in Figure 5a would produce a weak diffraction with opposite polarity to the reflected arrival (point 1 in Figure 5b). Such opposite-polarity returns are not clearly seen in the GPR data, suggesting that most observed diffractions are from sub-horizontal surfaces analogous to those simulated at point 2 in Figures 5a and 5b.

[15] The CPT/SPT/well profiling (Figure 2) across this terrain by Stewart and Parker [1992] shows that the 10–20m wide depressions in the semiconfining unit are punctuated by much steeper narrower conduits, a few meters in upper diameter, that extend to depths of several meters below the broader depression. These conduits play a crucial role in focusing groundwater recharge [Stewart and Parker, 1992], but their geometry represents a very difficult target for geophysical methods. There are nevertheless two good indications of these conduits within the 3D GPR survey. First, although the image of the broader depression is displayed for clarity as continuous in Figure 4, there are several indicators of conduits or dropdowns in the semiconfining unit. One example is shown with the points marked ‘3’ in Figure 5, where the top of the conduit appears as a reduced-amplitude return of crossing X’s in both the synthetic and unmigrated profiles, and as a lower amplitude zone of the semiconfining reflection on the migrated section. Second, approximately underlying some of the “gaps” in the semiconfining unit are weak but nevertheless distinct diffractions (circular on time slices) that represent reflecting...
points at depths up to 2 meters below the broader depression. One example is marked with ‘4’ in the Figure 5 profiles. These diffractions could, as illustrated in the synthetic model 5a, represent a “floor” to the conduit, and do collapse to bright points in the 3D migrations. These bright points are shallower in general than the base of the sand in the conduits as sketched by Stewart and Parker [1992] in Figure 2, but the sketched conduit bases are somewhat speculative in form and depth, and may not correspond directly to those imaged in Figure 5. Finally, it is interesting that the conduit indicated in Figure 5 is not centered beneath the deepest part of the broader depression. These sinkhole structures are clearly complicated.

Overall, the results of the GPR survey suggest that with refining, this technique may ultimately be useful for assessments of the hydrogeologic role of individual sinkholes. It is clear from this experience that imaging would be further improved by higher spatial resolution, cm-level topographic control, and a larger imaging area for better migration calculations.

4.2. Resistivity

The 2D resistivity profiles capture the overall geometry of the resistive fill over the conductive semiconfining unit (Figure 3). On inversions of both resistivity profiles the top of the semiconfining unit as imaged with GPR is coincident with the high-to-low transition in resistivity, which at the time of this survey was about 150 ohm-m (Figure 3). The overall good fit between the 2D resistivity and 3D GPR is clearly due to the relatively large lateral dimensions of the depression (~15 m) relative to the electrode spacings (~0.5–1 m) and depth to contact (~2–3 m).

The smaller scale, meter-sized anomalies in the resistivity profile in Figure 3a (eastern profile) diverge in form from the GPR-imaged semi-confining unit geometry. Resistivity images on the meter-scale are apparently complicated by 3D features, off-line structures, and noise. The resistivities are also clearly strongly influenced by factors beyond the depth to the semiconfining unit. For example, one of the most striking characteristics of the profiles is the contrast between the more resistive surficial sands outside the depression and the less resistive sands over the central depression. This pattern is not easily explained as an inversion artifact; it may instead indicate that sands over the depression are wetter or, where saturated, more porous. Enhanced porosity is expected, as these sands are raveling downward into the sinkhole. Vegetation is concentrated around the outside of the depression, which may further enhance relatively drying of soils outside the depression.

There is no indication of high-resistivity conduits underlying the central depression imaged by the resistivity profiles (Figures 3 and 4). Simulations confirm that a 2 to 4 meter diameter high-resistivity sand-filled conduit extending 2.3 meters beneath a 15-m diameter conical depression would be essentially invisible to the 2D survey geometries used in this case study, as well as to dipole-dipole geometry surveys. Smoothing due to regularization during the inversion of resistivity data presumably contributes to the “invisibility”. Differences between models with and without conduits are less than a few percent, assuming a resistivity of 200 ohm-m over the semiconfining unit and a resistivity of 20 ohm-m for the semiconfining unit and below. Whether geometrically optimized 3D resistivity surveys with larger footprints could yield more information is a topic for future study.

In contrast to other surveys described in the literature [e.g., El-Behiry and Hanafy, 2000; Labuda and Baxter, 2001; Ahmed and Carpenter, 2003], beneath this sinkhole there is no indication of a broader fracture zone. Resistivities underlying the broader depression are similar to those at depth outside the sinkhole (Figure 3a).

5. Conclusions

GPR and resistivity methods are found to provide consistent overall images of a 15-m diameter sinkhole in the covered karst terrain of west-central Florida. The target imaged by both methods is not the top of limestone, but the depression in the clay-rich semiconfining layer that underlies clean surface sands. Based on our data, it appears that the 3D GPR-survey can additionally detect vertical undulations of 10–20 cm in the semiconfining layer as well as conduits (~1–4 meters across) underlying sinkhole surface fill that extend some 2 meters down below the base of the central depression. 2D resistivity surveys with the geometry used here do not appear capable of detecting such conduits and meter-scale features in the semiconfining unit.

These results indicate that high-resolution GPR surveys hold promise for imaging portions of sinkholes of hydrogeologic significance. Such GPR surveys, coupled with high-resolution ground-truthing, are desirable to better assess this method.

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