Resistivity Imaging and Natural Potential Applications to the Antioch Fault Zone in the Onion Creek / Barton Springs Segment of the Edwards Aquifer, Buda, Texas

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ABSTRACT

Resistivity imaging and natural potential (NP) surveys were conducted in the vicinity of Antioch Cave, the largest recharge feature in the bed of Onion Creek within the Barton Springs segment of the Edwards Aquifer. Site-scale geologic mapping of the study area indicates a fault zone bound by two faults crossing Onion Creek: 1) the western fault occurs within the Georgetown Formation, and 2) the eastern fault occurs within the Buda Limestone. Both faults show tilted bedding across a total fault-bounded zone with a width about 500 ft and about 100 ft of estimated throw. This geophysical work characterizes the geometry of the geologic units, the throw of the individual fault (s), and identifies possible karstic features within the fault zone.

Two 1100 ft long resistivity and NP transects were run parallel to the north and south banks of Onion Creek and across the fault zone. Resistivity results show chaotic fault zone deformation in the vicinity of the western portion of the fault zone where the Georgetown Formation is juxtaposed against the Del Rio Clay with about 50 ft of throw. Resistivity results on the eastern fault indicate a discrete fault where the Del Rio Formation is juxtaposed, with the Buda Limestone and about 40 ft of throw. The Del Rio is about 25 ft thick on the upthrown side and about 100 ft of apparent thickness on the downthrown side. The resistivity results from the southern bank of the creek also appear to indicate that the Del Rio Formation terminates at about station 960 ft along the profile and at a depth of about 65 ft. Additional surface geological observations along Onion Creek also suggest the existence of an unmapped fault in that vicinity. NP results confirm karstic anomalies across Antioch Cave along the northern bank, where Antioch Cave is known to extend, and additional high and low NP anomalies across the Edwards units that may indicate additional karstic features at depth.

INTRODUCTION

Geophysical methods are occasionally used to characterize karstic features (caves, sinkholes, faults, and fractures) prior to any hydrogeological or geotechnical studies in the Austin area. Opinions concerning the effectiveness of these geophysical surveys are mixed, and geophysical techniques are not generally recognized as primary tools in karstic studies. However, advances in the manufacturing of geophysical instruments over the last ten years have made geophysics a viable tool for geotechnical studies of these karstic features. Data quality has

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been increased with the advent of continuous data collection. The data are better processed and interpreted by new and improved software packages, which produce improved subsurface imaging and mapping.

In this study, the authors demonstrate the utility of integrated geophysical surveys (resistivity and natural potential) co [NP]mbined with surface geologic mapping for the subsurface characterization of geologic units, fault zones, and karstic features.

The study area is located in the Barton Springs segment of the Edwards Aquifer and in the vicinity of Antioch Cave, which is located within Onion Creek and near the town of Buda (Fig. 1). The study area traverses the eastern-most edge of the recharge zone and the confined zone of the Edwards Aquifer (Figs. 1 and 2). Antioch Cave is the largest capacity recharge feature within the Barton Springs segment of the Edwards Aquifer. A recharge enhancement structure has been constructed over the cave and is discussed in Smith et al. (2011). Understanding the geometry of the geologic units and faulting has implications on the extent of the recharge zone boundary and the permeability architecture of the recharge feature and aquifer in the study area.

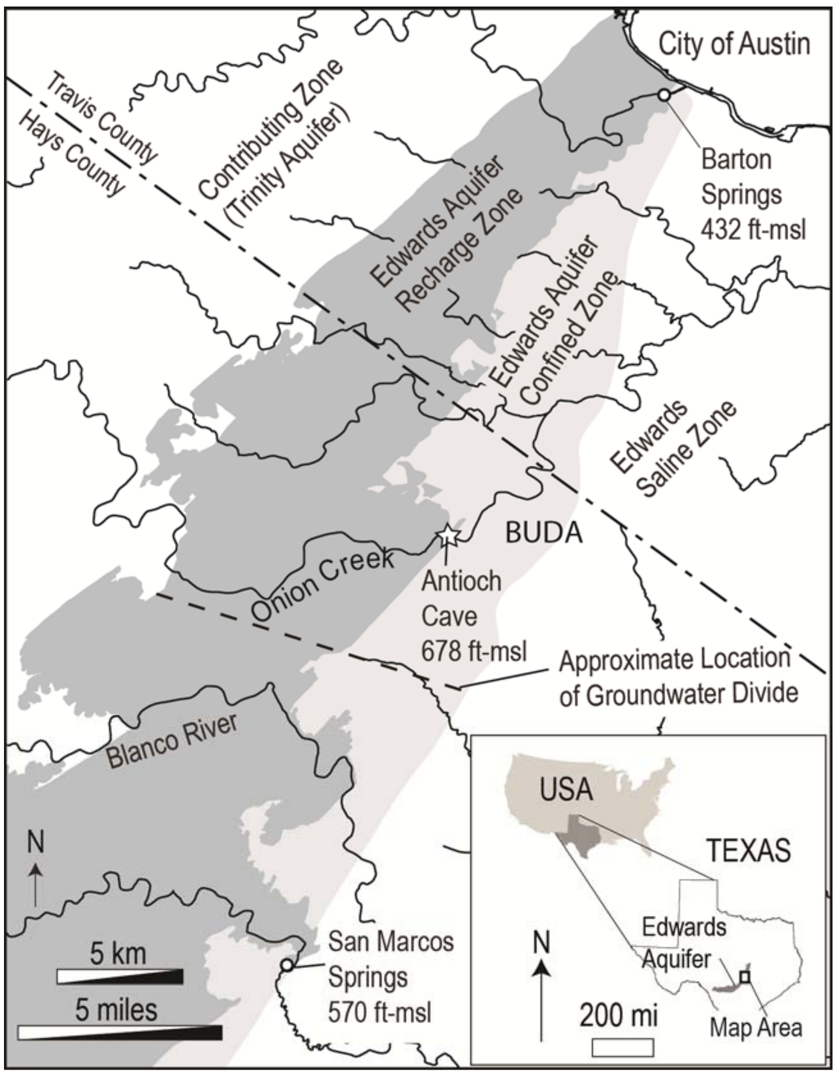

Figure 1. Site map indicating the location of Antioch Cave in the Barton Springs segment of the Edwards Aquifer, Texas.

GEOLOGY AND STRUCTURE

Figure 2 displays the general bedrock geology of the study area and beyond. The map indicates the location of Antioch Cave and a significant fault in the middle of the map that is the boundary eastern boundary of the recharge zone.

The surface geological units in the study area consist of (stratigraphically from the bottom to the top, stratigraphically from bottom to top): the Georgetown Formation, Del Rio Clay, Buda Limestone, and alluvium. The Edwards Group limestones are not exposed at the surface in the study area. Much of the study area is overlain by Quaternary alluvium and terrace deposits and disturbed sediments resulting from gravel mining and associated activities. Figure 3 provides a detailed geological outcrop map of the study area, and shows the Antioch Cave, two major down-to-the-east normal faults along with several minor fractures, and an apparent sinkhole located in the bed of Onion Creek. A multiport monitor well shown in Figure 3 provides subsurface stratigraphic control for the eastern portion of the study area.

The study area is located within the Balcones Fault Zone of Central Texas. These faults are Miocene-age normal faults that trend predominantly northeast-southwest and are generally downthrown to the southeast. The elevation of the top of the Edwards Group is known from exposures within Antioch Cave (639 ft-msl [ft above mean sea level]) and also from borehole geophysical logs from the multiport well (538 ft-msl) indicating about 100 ft of throw across the mapped fault (Fig. 2).

The Edwards Aquifer is composed of the Edwards Group limestones and the Georgetown Formation. The Edwards Group limestones consist of light gray, dense, thick-bedded dolomitic limestones with chert. The Edwards Group is a highly karstic limestone. The Georgetown Formation crops out on the west side of the study area and includes Antioch Cave. The Georgetown is about 50 ft thick and consists of alternating beds of thin, fine-grained limestone and marly fossiliferous limestone. The Del Rio Clay overlies the Georgetown Formation and is the primary confining unit of the Edwards Aquifer. The Del Rio Clay is about 50 ft thick in the study area and consists of dark blue-green to yellow-brown gypsiferous clay. The lower boundary of the Del Rio is gradational with the Georgetown Limestone, and the transition occurs through several feet. The Buda Limestone overlies the Del Rio Clay and is about 40 ft in the study area. The Buda limestone is a dense, variably nodular "porcelaneous" limestone (Small et al., 1996). The Eagle Ford is not exposed in the study area.

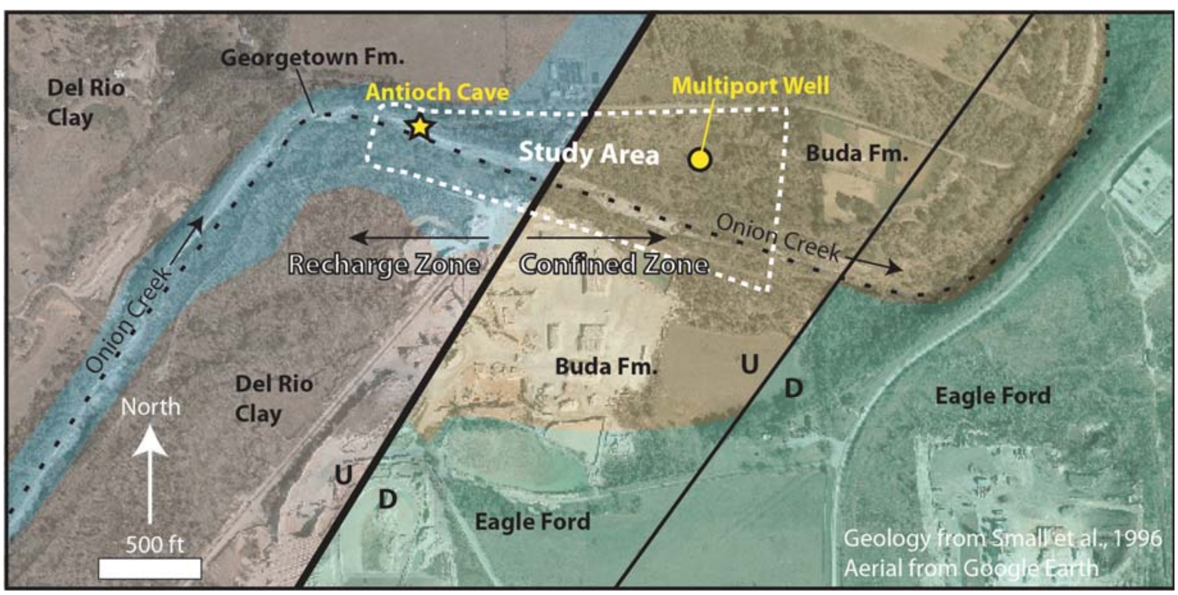

Figure 2. Bedrock geologic map of the geophysical study area, that is shown with a dashed white line. Note the location of the Antioch Cave to the west in the Onion Creek bed. Geology from Small et al., (1996).

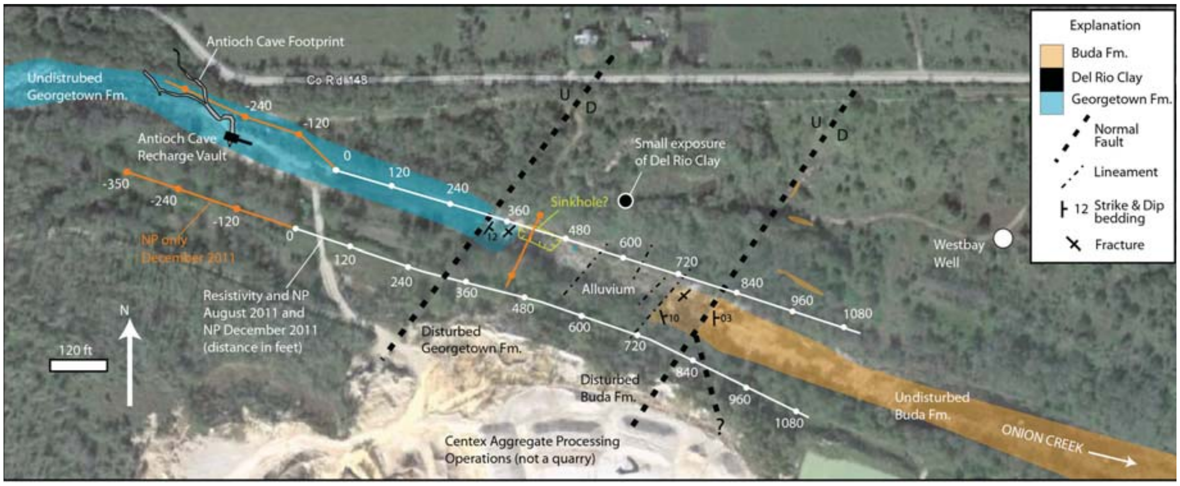

Figure 3. A detailed geological outcrop map of the geophysical study area. The map indicates two significant faults crossing the Onion Creek along with several lineaments. Note the locations of the geophysical profiles on the northern and southern banks of the Onion Creek. A natural potential survey was also performed across the suspected sinkhole.

Figure 2 illustrates the fault and fracture control on the geomorphology of Onion Creek in the vicinity of the study area. The creek trends to the northeast for several thousand feet, makes a right angle turn and extends linearly to the southeast for several more thousand feet, and makes another right angle bend back to the original northeast trend. The northeast trend of the creek is parallel to the regional strike of Balcones faulting and also to the fault zones in the study area. The southeast trending section of the creek may be following a southeast trending fracture system or faulting, perpendicular to the dominant faulting trend. Conjugate fault and fracture systems are very common in the Balcones Fault Zone (Ferrill et al., 2004). Therefore, it is possible that the southeast trending section of Onion Creek is following an unmapped fault in that orientation, although other than the geomorphology, no other surface or subsurface data suggest that one exists at this time.

GEOPHYSICAL SURVEYS

Resistivity and NP methods were chosen to characterize the subsurface geology and its related faults in the study area for their ability to rapidly map electrical resistivity and ambient electrical current, respectively. These attributes are often useful in geological facies identification.

Resistivity Method

Resistivity imaging aims to build up a picture of the electrical properties of the subsurface by passing an electrical current along electrodes and measuring the associated voltages. This technique has been used widely in determining karst features, such as voids, and subsurface structures, such as faults and fractures (Carpenter, 1998; Ahmed and Carpenter, 2003; Dobecki and Upchurch, 2006; Saribudak, 2011a, 2011b).

In this study, we used Advanced Geoscience Inc.'s (AGI) SuperSting R1 resistivity meter with dipole-dipole resistivity technique that is more sensitive to horizontal changes in the subsurface, and provides a 2D electrical image of the near-surface geology. Electrode spacing was held to 20 ft along all profiles. The depth of the investigation was approximately 130 ft.

We collected roll-along resistivity data across the study area in an ESE orientation, perpendicular to the strike of the fault zone. After the initial section of resistivity data was collected, the first cable of 14 electrodes was moved ahead of the survey line. This process was continued until all data along the desired length were collected. The data from the roll-along can be combined into a single apparent-resistivity dataset during processing. Appropriate quality assurance/quality control procedures such as testing contact resistance before data collection was performed for each segment of each profile. Contact resistance measures the resistance to current flow at electrodes caused by imperfect electrical contact with the earth. Poor data quality or anomalous data can result from high or highly variable electrode contact resistance along a profile. To decrease the effect of contact resistance along each profile, we poured a saltwater solution into the base of each electrode before the contact test was performed.

Natural Potential Method

Natural electrical (NP) currents occur everywhere in the subsurface. In seepage or cave investigations, we are concerned with the unchanging or slowly varying direct currents (DC) that give rise to a surface distribution of natural potentials due to the flow of groundwater within permeable materials (Lange and Kilty, 1991; Lange, 1999; Vichabian and Morgan, 2002; Saribudak, 2011a, 2011b). Differences of potential are most commonly in the millivolt range and can be detected using a pair of non-polarizing electrodes and a sensitive measuring device (i.e., a voltmeter). It should be noted that water movement should be present within or surrounding a cave in order to determine a void or cave location. Positive and negative NP values are attributed to changes in the flow conditions and the resistivity distribution of the subsurface. The source of NP anomalies can be also due to changes in topography, soils, and rock conditions. It should be noted that NP measurements made on the surface are the product of electrical current due to groundwater flow and the subsurface resistivity structure.

Field Survey Design

Two 1100 ft resistivity and NP profiles were surveyed parallel to the southern and northern banks of Onion Creek separated by about 150 ft. Locations of these profiles are shown with white lines in Figure 3. The station spacing on both the resistivity and NP surveys was 20 ft. These surveys were conducted during the month of August 2011 while record-setting hot and dry conditions prevailed across the entire State of Texas. For this reason, the authors performed additional NP profiles at the same station spacing in December, 2011 when recent rains had brought some relief from drought conditions to the area. These two NP profiles were extended about 400 ft further to the west to cover the location of Antioch Cave (Fig. 3). In addition, a NP profile was surveyed across a suspected sinkhole feature within the bed of Onion Creek bed (Fig. 3). It should be noted that the same base station was used on both NP surveys.

RESISTIVITY IMAGING RESULTS

The resistivity profiles surveyed along the northern and southern banks of Onion Creek are given in Figures 4 and 5, respectively. Both figures include un-interpreted and interpreted resistivity sections. Resistivity values of the section are fixed between 10 and 700 ohm-m, so that both resistivity sections can be correlated. Low resistivity values are shown with a blue color, which corresponds to the Del Rio Formation and the rest of the colors (green, yellow, and red) colors are attributed Georgetown, Edwards Aquifer units, and Buda Limestone, respectively.

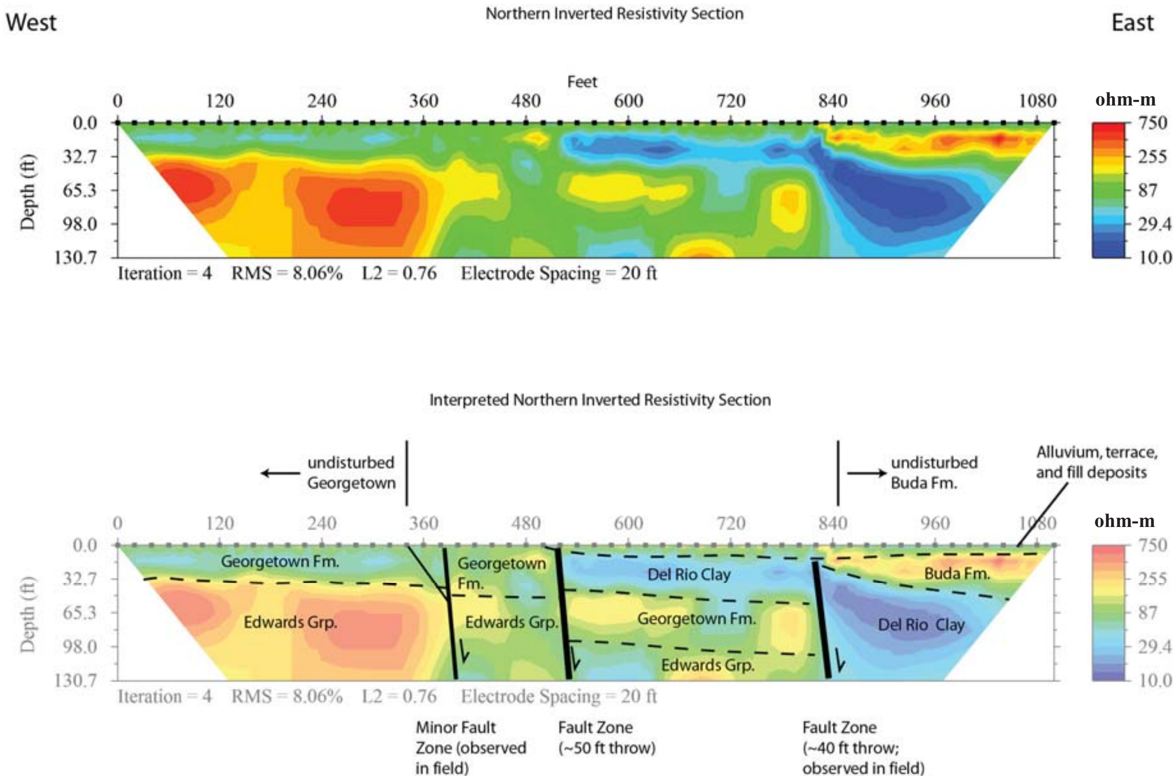

Figure 4. Resistivity imaging data along the northern bank of the Onion Creek. The lower and upper resistivity sections are given with and without the geological interpretation, respectively.

Resistivity Profile along Northern Bank

The resistivity imaging data along the northern bank displays the uninterpreted and interpreted resistivity data (Fig. 4). The location of the outcropped Georgetown Formation is shown with the green color in the northwestern part of the profile. Underlying the Georgetown Formation are the Edwards Group units, which are displayed with yellow and red colors. The contact between the Edwards Group units and the Georgetown Formation appears to be quite well-defined. However, this conformity disappears at about 360 ft along the resistivity section where the first fault is observed in the field. Furthermore, there is a chaotic disturbed zone in the subsurface between stations 360 and 540 ft. In order to explain the resistivity structure of the geological units, two faults are projected at stations 360 and 540 ft. The first fault, which is observed in the field and by resistivity data at 360 ft strikes north-northeast, occurs within the Georgetown Formation. The second fault, predicted by the resistivity data, strikes to the northeast and juxtaposes the Georgetown and Del Rio formations. This second fault is obscured by alluvium at the surface.

There is a relatively undisturbed resistivity section between stations 540 and 760 ft where a low resistivity unit (Del Rio Formation) is observed at about 15 ft below the surface. It should be noted that the surface geology between those stations is identified as alluvium. The resistivity data indicate a significant fault at about station 820 ft which approximately corresponds to the observed fault location in the study area (Fig. 3). The resistivity data indicate that the fault juxtaposes the Del Rio formation against the Buda Limestone. The Del Rio Formation has a thickness of about 20 ft on the upthrown side of the fault (northwest direction) whereas it has 100 ft apparent thickness on the downthrown side. In addition, the Del Rio Formation appears to be deformed and folded along the fault plane. This deformation could account for the increase in apparent thickness.

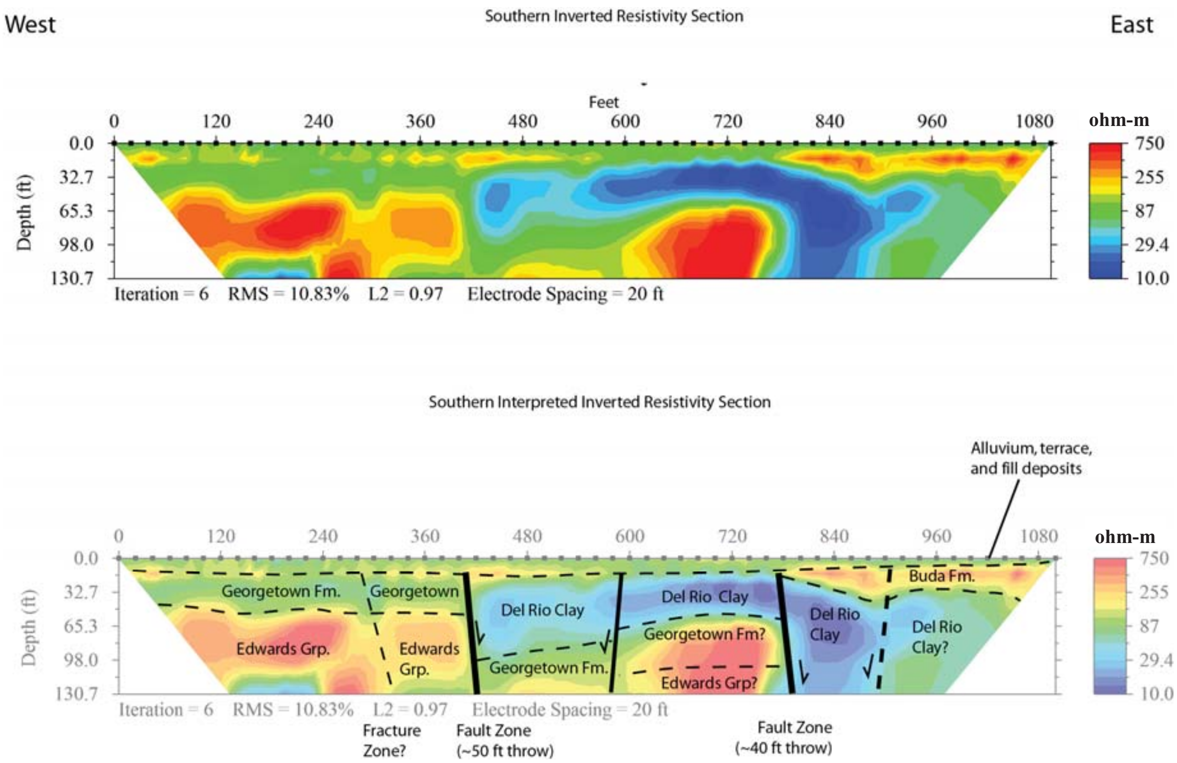

Figure 5. Resistivity imaging data along the southern bank of the Onion Creek. The lower and upper resistivity sections are given with and without the geological interpretation, respectively.

Resistivity Profile along Southern Bank

The resistivity data taken along the southern bank of Onion Creek are shown in Figure 5. The resistivity data indicate very similar anomalies that are observed along the northern bank profile. The resistivity data indicate a fault at station 400 ft which juxtaposes the Georgetown Formation and the Del Rio Clay. There is a highly disturbed zone between stations 360 and 600 ft where very low resistivity anomalies are observed. The second fault limiting the chaotic zone is located at station 600 ft. This fault strikes to the northwest and is interpreted as a down to the SE normal cross-fault (Fig. 5). Between stations 600 and 740 ft, the Del Rio Formation (blue color on the resistivity section) is observed at about 15 ft below the surface. The unit has a thickness of 20 ft and is underlain by the Georgetown Formation (green to red in color). The apparent increase in resistivity of the Georgetown Formation at this location is not clear. Either the Georgetown Formation is unusually thin and the red color corresponds to the Edwards Group, or there are significant voids or other factors influencing resistivity. Another significant fault is displayed at station 780 ft. This fault juxtaposes the Del Rio Formation and Buda Limestone. The Del Rio Formation appears to be deformed proximal to the fault plane producing an increase in apparent thickness. A change in the resistivity suggests the Del Rio Clay is pinched or faulted out at about 920 ft at a depth of 30 ft. It should be noted that the topographic elevation of station 960 ft is about 15 ft above the bed of Onion Creek where the Buda Limestone outcrops. Thus, we examined the bed of Onion Creek for a corresponding Del Rio Formation pinch out. A photograph taken at about station 840 ft shows horizontal Buda Limestone layers juxtaposed against steeply-dipping Buda Limestone layers along what is interpreted to be a fault. The location shown in the photograph and the corresponding resistivity data, which are extracted from the original resistivity data, are given in Figure 6. It should be noted that the resistivity profile is reversed in direction to be compatible with the orientation of the photograph. In order to explain the termination of the Del Rio Clay, a fault is interpreted at station 920 ft.

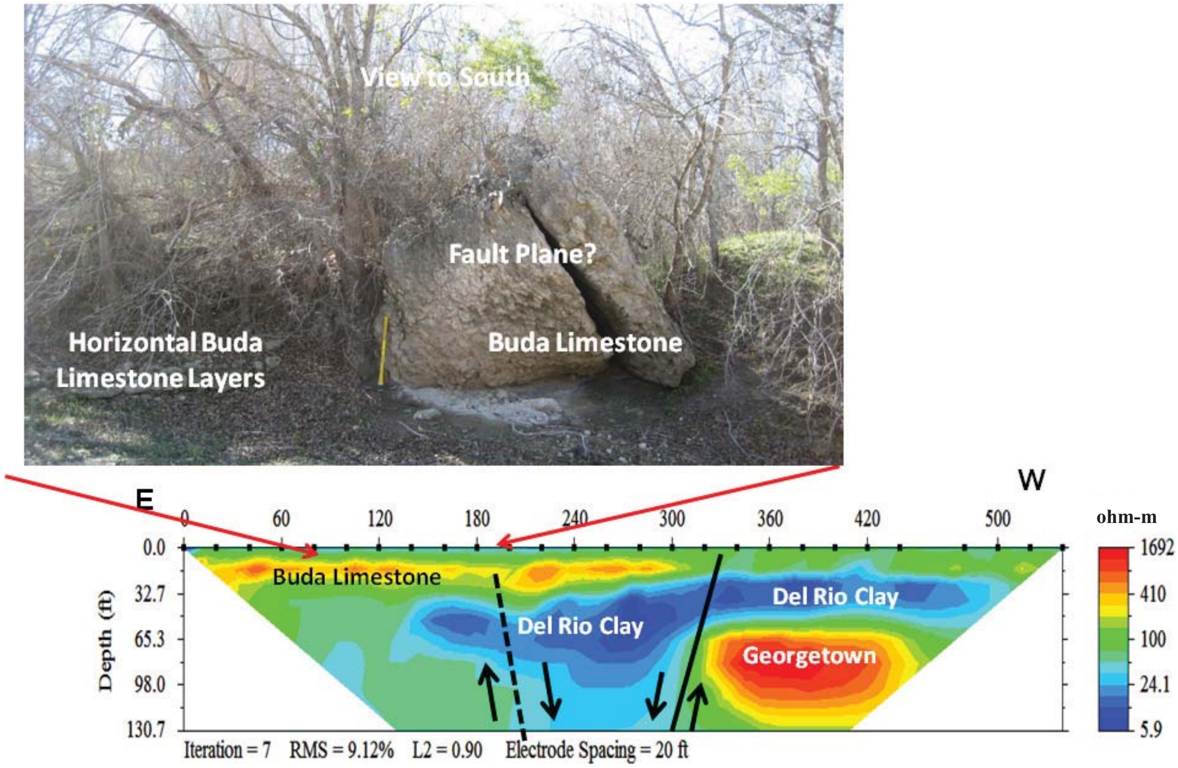

Figure 6. The photo shows steeply-dipping Buda Limestone beds juxtaposed against the horizontal Buda Limestone beds. A fault is inferred at this location and corresponding to the location where the Del Rio Clay is terminated in the subsurface. A resistivity section (lower section), that is segmented from the original resistivity section (Fig. 4) shows where the Del Rio Clay pinches out with respect to the field picture.

NATURAL POTENTIAL (NP) RESULTS

A total of three NP profiles were collected in the study area along the same transect as the resistivity. Two of the NP profiles were surveyed along the northern and southern banks of Onion Creek, and the third NP dataset was collected across Onion Creek where an apparent sinkhole was located (see Figure 3). It should be noted that the NP profiles along the banks of the creek were collected twice (August, 2011 and December, 2011) to differentiate the effects of the drought and the rainy season on the NP data. In December, profiles were extended about 400 ft further to the west to cover the location of the Antioch Cave. The NP data collected in December are discussed below.

NP Data along the Northern and Southern Banks

Both NP datasets acquired along the northern and southern banks of Onion Creek during December, 2011 are shown in Figure 7. The northern data sets indicate karstic anomalies between stations -120 and -320 ft. It is known that Antioch Cave extends toward station -320 ft. The karstic anomaly observed at -120 ft could also be due to an unknown chamber of the cave. Furthermore, additional karstic anomalies are observed between 300 and 500 ft where the first significant fault is observed on the resistivity section (Fig. 4). This fault juxtaposes the Georgetown Formation against the Del Rio Clay. In addition, a fault-like NP anomaly ("S"-like anomaly) ob-

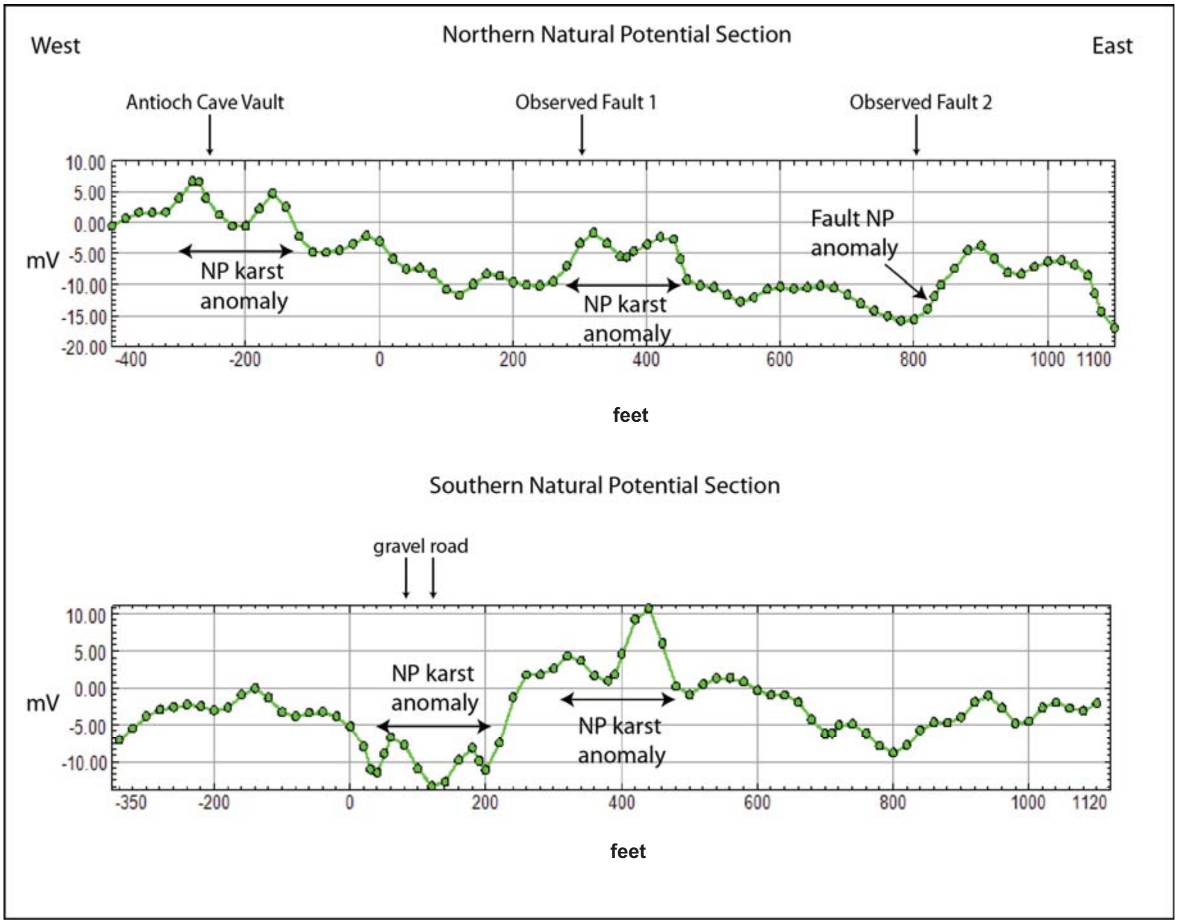

Figure 7. Natural potential data along the northern and southern banks of the Onion Creek. Note the locations of two significant faults observed in Figure 3. Significant NP anomalies are marked on both profiles.

served between stations 780 and 900 ft corresponds to where the second significant fault is observed. This fault brings the Del Rio Clay and Buda Limestone in contact.

The NP data collected along the southern bank of Onion Creek also indicates karstic anomalies (see lower NP cross section in Figure 7). A pair of high and low NP anomalies is observed between stations 0 and 200 ft. These anomalies do not exist on the corresponding stations of the northern NP section. A significant NP gradient is observed between stations 200 and 300 ft and more NP anomalies are located between stations 300 and 500 ft. Locations of all these NP anomalies correspond to the significant fault or fault zone are observed on the geological map and the resistivity sections (Figs. 3 and 5).

NP Data over the Apparent Sinkhole

Figure 8 shows the NP profile surveyed across an apparent sinkhole which is located in Onion Creek between northern transect stations 360 and 380 ft (Fig. 3). The NP data indicate a significant negative anomaly (~ -8 mV) between stations 20 and 60 ft where the sinkhole is located. This anomaly can be explained by the downward movement (recharge) of groundwater into the sinkhole.

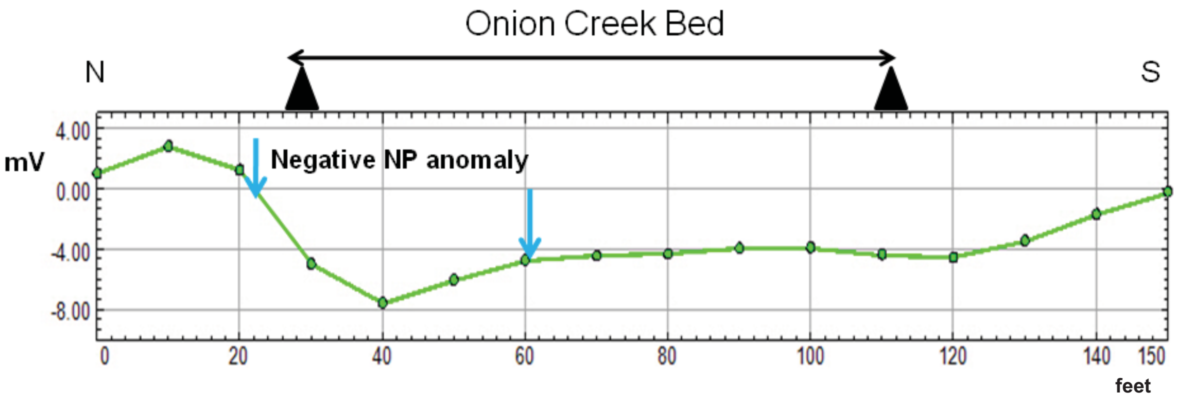

Figure 8. Natural potential data across the Onion Creek where a sinkhole is suspected. Note the negative NP anomaly near the northern bank of the Creek.

DISCUSSION AND CONCLUSIONS

Geological information inferred from the resistivity and the NP data (Figs. 4, 5, and 7) was combined with the geological map of the study area (Fig. 3) and is presented in Figure 9. Based on the resistivity data, the locations, orientations, and geometries of the fault zone crossing Onion Creek are better defined.

The NP data show anomalies that are present mostly within the Georgetown Formation and the underlying Edwards Group. The NP data also display anomalies in the vicinity of Antioch Cave. Another significant NP anomaly is observed across Onion Creek where a sinkhole is suspected based on surface expressions. The NP data over the suspected sinkhole indicate a significant negative anomaly, as expected over sinkholes.

In summary, integrated geophysical results combined with the geological data indicate that geophysical methods can be used successfully to map stratigraphy and structure (faults and fractures) over the Edwards Aquifer and the overlying geological formations such as the Del Rio Clay and Buda Limestone.

This study provides details as to the geometry of the eastern extent of the recharge zone in the study area, which has implications for land use practices. In addition, the study could provide a framework for understanding how the movement of groundwater is influenced by faulting in the Edwards Aquifer.

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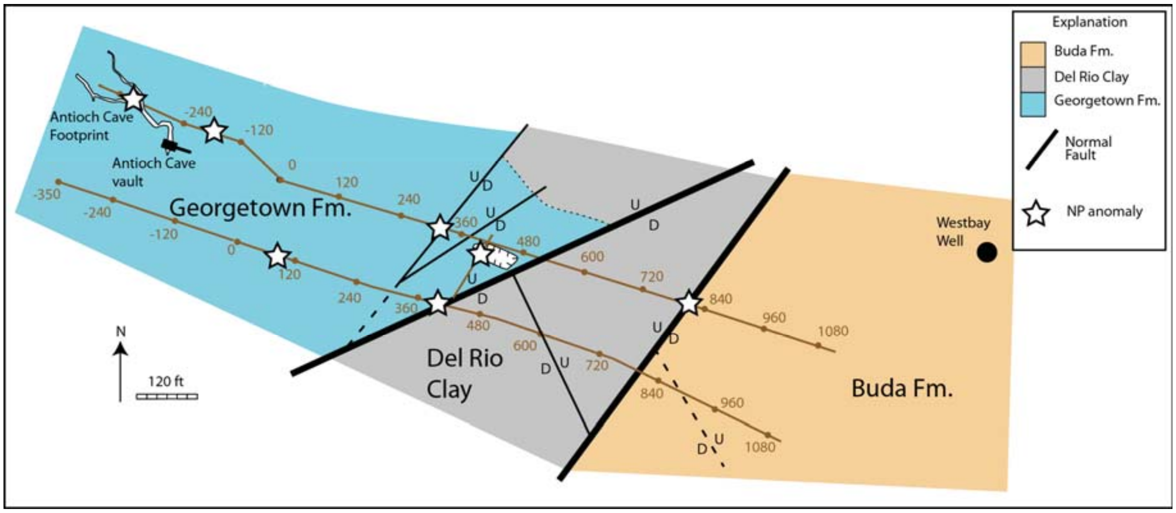

Figure 9. Revised geological outcrop map based on the geophysical data. Note the locations of the NP anomalies which are shown by the stars.

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NOTES