Geophysical Delineation of the Freshwater/ Saline-Water Transition Zone in the Barton Springs Segment of the Edwards Aquifer, Travis and Hays Counties, Texas, September 2006

By Jason D. Payne, Wade H. Kress, Sachin D. Shah, James E. Stefanov, Brian A. Smith, and Brian B. Hunt

In cooperation with the Barton Springs/Edwards Aquifer Conservation District

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Conversion Factors, Abbreviations, and Datums

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.02832	square meter (m^2)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (km)	3.281	foot (ft)
	Area	
square meter (m^2)	10.76	square foot (ft^2)

Abbreviations

BSEACD, Barton Springs/Edwards Aquifer Conservation District

DS, dissolved solids

GIS, geographic information system

milligrams per liter, mg/L

ohm-meter, ohm-m

RMS, root mean square error

TDEM, time-domain electromagnetic

USGS, U.S. Geological Survey

Datums

Sounding data: Vertical coordinate information is referenced to North American Vertical Datum of 1988 (NAVD 88).

Geologic sections: Vertical coordinate information is referenced to National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to North American Datum of 1927 (NAD 27) or 1983 (NAD 83).

Geophysical Delineation of the Freshwater/Saline-Water Transition Zone in the Barton Springs Segment of the Edwards Aquifer, Travis and Hays Counties, Texas, September 2006

By Jason D. Payne[1], Wade H. Kress[1], Sachin D. Shah[1], James E. Stefanov[1], Brian A. Smith[2], and Brian B. Hunt[2]

Abstract

During September 2006, the U.S. Geological Survey, in cooperation with the Barton Springs/Edwards Aquifer Conservation District, conducted a geophysical pilot study to determine whether time-domain electromagnetic (TDEM) sounding could be used to delineate the freshwater/saline-water transition zone in the Barton Springs segment of the Edwards aquifer in Travis and Hays Counties, Texas. There was uncertainty regarding the application of TDEM sounding for this purpose because of the depth of the aquifer (200–500 feet to the top of the aquifer) and the relatively low-resistivity clayey units in the upper confining unit. Twenty-five TDEM soundings were made along four 2–3-mile-long profiles in a study area overlying the transition zone near the Travis-Hays County boundary. The soundings yield measurements of subsurface electrical resistivity, the variations in which were correlated with hydrogeologic and stratigraphic units, and then with dissolved solids concentrations in the aquifer. Geonics Protem 47 and 57 systems with 492-foot and 328-foot transmitter-loop sizes were used to collect the TDEM soundings. A smooth model (vertical delineation of calculated apparent resistivity that represents an estimate [non-unique] of the true resistivity) for each sounding site was created using an iterative software program for inverse modeling. The effectiveness of using TDEM soundings to delineate the transition zone was indicated by comparing the distribution of resistivity in the aquifer with the distribution of dissolved solids concentrations in the aquifer along the profiles. TDEM sounding data show that, in general, the Edwards aquifer in the study area is characterized by a sharp change in resistivity from west to east. The western part of the Edwards aquifer in the study area shows higher resistivity than the eastern part. The higher resistivity regions correspond to lower dissolved solids concentrations (freshwater), and the lower resistivity regions correspond to higher dissolved solids concentrations (saline water). On the basis of reasonably close matches between the inferred locations of the freshwater/saline-water transition zone in the Edwards aquifer in the study area from resistivities and from dissolved solids concentrations in three of the four profiles, TDEM sounding appears to be a suitable tool for delineating the transition zone.

Introduction

The Barton Springs segment of the Edwards aquifer in Travis and Hays Counties, Texas (fig. 1) is an important resource for municipal, industrial, domestic, recreational, and ecological water supply. The concentration of dissolved solids (DS), or salinity, in water in the aquifer increases from west to east, resulting in a zone of transition from freshwater (DS concentration less than 1,000 milligrams per liter [mg/L]) to saline water. The freshwater/saline-water interface thus is defined as the 1,000-mg/L DS concentration threshold.

During September 2006, the U.S. Geological Survey (USGS), in cooperation with the Barton Springs/Edwards Aquifer Conservation District (BSEACD), conducted a geophysical pilot study to determine whether time-domain electromagnetic (TDEM) sounding could be used to delineate the freshwater/saline-water transition zone in the Barton Springs segment of the Edwards aquifer. TDEM sounding (Fitterman and Labson, 2005) is one of a number of surface-geophysical methods used to characterize subsurface geologic and hydrogeologic properties. TDEM sounding can be used to detect variations in electrical resistivity of the subsurface that can be related to variations in the physical and chemical properties of soil, rock, and pore fluids. This application of TDEM sounding also was a test to indicate whether high-quality data could be obtained from the required depths (200–500 feet [ft] to the top of the aquifer plus a substantial

[1] U.S. Geological Survey.

[2] Barton Springs/Edwards Aquifer Conservation District.

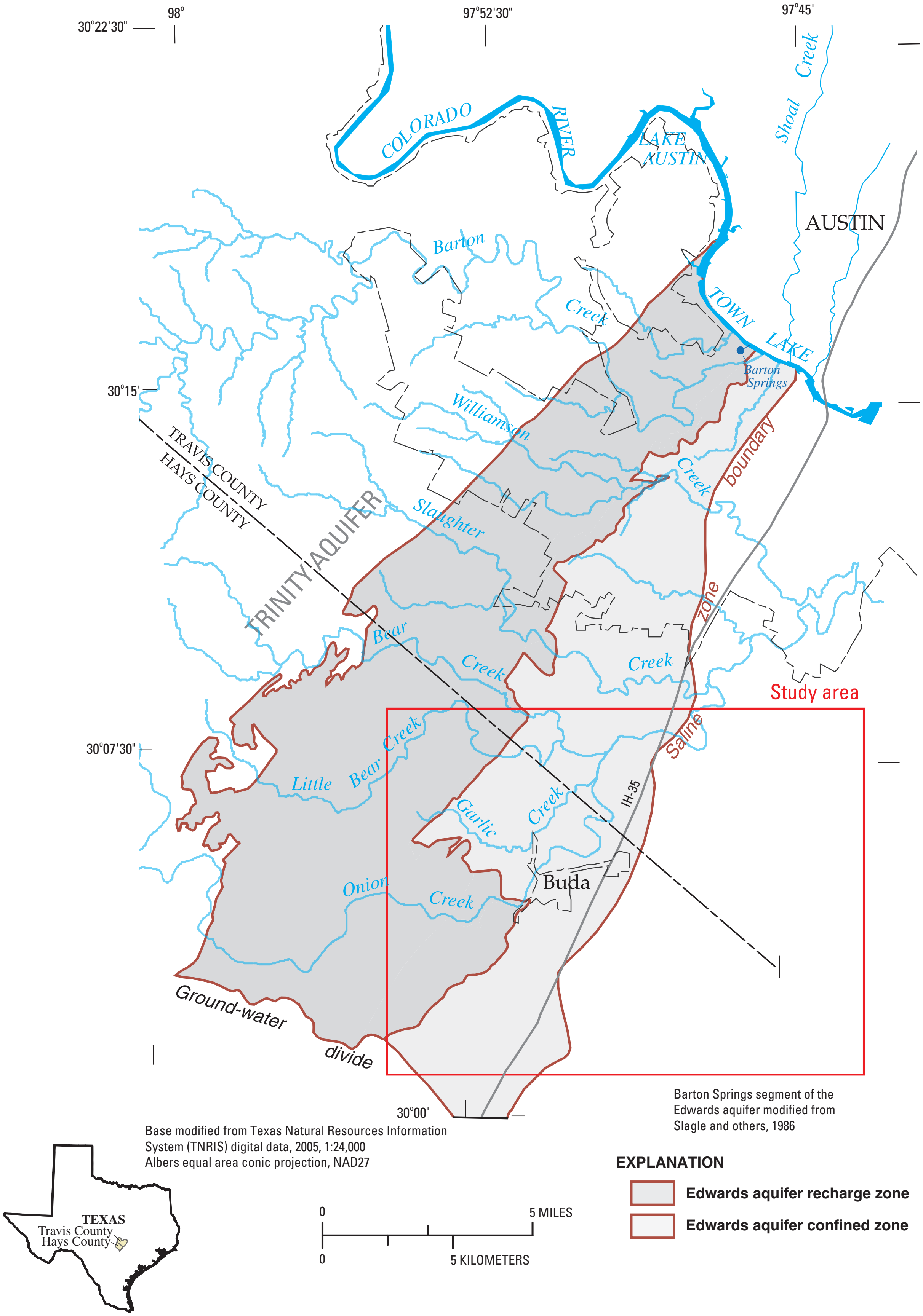


Figure 1. Location of Barton Springs segment of the Edwards aquifer and study area, Travis and Hays Counties, Texas.

thickness of the aquifer); and whether relatively low-resistivity (relatively high-conductivity) clayey units that compose the upper confining unit of the aquifer would adversely affect the ability of TDEM to detect relatively high-conductivity saline water that indicates the transition zone. The pilot application of TDEM sounding also was an opportunity to test whether urban features would adversely affect the sounding data. Power lines associated with certain frequencies, nearby radio and radar transmitters, metallic structures, and buried metal objects can cause noise in TDEM measurements (Lucius and others, 2007).

Twenty-eight sites were selected for TDEM sounding across four profiles (one of which comprises two alternative lines) in a study area overlying the transition zone of the aquifer in Travis and Hays Counties (fig. 2). The TDEM profiles were about 2–3 miles (mi) long. Because of land-access difficulties at two sites and equipment malfunction at another, data from three of the original 28 sites were not collected. Twenty-five TDEM soundings (measurements) (table 1) were used for this report.

Purpose and Scope

This report documents a pilot study in the Barton Springs segment of the Edwards aquifer done in September 2006 to determine whether TDEM sounding can be used to delineate the freshwater/saline-water transition zone in the aquifer. There was uncertainty regarding the application of TDEM for this purpose because of the depth of the aquifer and the relatively low-resistivity clayey units in the upper confining unit. The report describes the results of 25 TDEM soundings along four profiles across the transition zone. Data were collected during September 2006. The soundings yield measurements of subsurface electrical resistivity, the variations in which are correlated with hydrogeologic and stratigraphic units, and then with DS concentrations in the aquifer. The report briefly describes the aquifer, upper confining unit, and study area; and briefly describes TDEM theory and its application to characterize properties of the subsurface. The interpretation of subsurface resistivity, aided by selected borehole geophysical data, is discussed. The data for each profile are shown as two-dimensional subsurface sections of resistivity generated from one-dimensional inverse modeling results and compared graphically with an associated geologic section and plan view of DS concentrations along the profile.

Previous Investigations

Previous investigations that describe the regional setting, hydrogeologic characteristics, and electrical stratigraphy of the area were used as guidance for this study. Smith and others (2003) conducted a helicopter electromagnetic survey across the freshwater/saline-water transition zone in the Seco Creek area in Medina County about 60 mi southwest of the study area. Data from that report were used to identify apparent resistivity ranges for each of the stratigraphic units in the study area.

Baker and others (1986) describes the regional geologic setting and hydrogeologic characteristics of the Edwards aquifer in the Austin area. That report was used to locate the freshwater/saline-water transition zone and to determine required depths of investigation at different points across each profile. Maclay (1995) presents a comprehensive study of the geology and hydrogeology of the Edwards aquifer in the San Antonio area that includes the Barton Springs segment. Small and others (1996) conducted a study to characterize the geologic framework and hydrogeologic characteristics of the Edwards aquifer in northeastern Hays and southeastern Travis Counties. Both reports provided information on the geologic characteristics of the study area.

Table 1. Location data for time-domain electromagnetic soundings used for this report, Barton Springs segment of the Edwards aquifer, Travis and Hays Counties, Texas.

Profile	Site identifier (fig. 2)	Easting (feet)	Northing (feet)	Altitude (feet above NAVD 88)
2	200	2,013,702	10,936,180	634.20
2	240	2,018,195	10,931,173	740.71
2	245	2,019,691	10,930,398	706.88
2	247	2,020,355	10,930,018	706.92
2	250	2,021,358	10,930,533	681.51
2	260	2,023,146	10,930,023	665.34
3	320	2,010,614	10,921,904	707.95
3	330	2,013,558	10,918,985	754.75
3	340	2,015,854	10,919,689	744.20
3	350	2,018,280	10,920,862	722.11
3	360	2,021,176	10,921,365	751.63
3	370	2,023,325	10,922,600	752.60
4.1	410	2,004,443	10,909,101	742.70
4.1, 4.2	420	2,012,228	10,908,088	693.72
4.1, 4.2	440	2,006,948	10,910,110	736.82
4.1, 4.2	450	2,008,527	10,909,042	706.76
4.1, 4.2	460	2,010,612	10,909,099	692.00
4.2	470	2,005,533	10,912,378	739.23
5	520	2,001,415	10,902,646	711.76
5	522	2,001,850	10,903,909	727.65
5	524	2,003,092	10,904,189	757.70
5	530	2,005,478	10,905,299	742.70
5	540	2,006,559	10,904,444	715.35
5	550	2,008,722	10,904,029	696.57
5	560	2,009,319	10,904,949	727.43

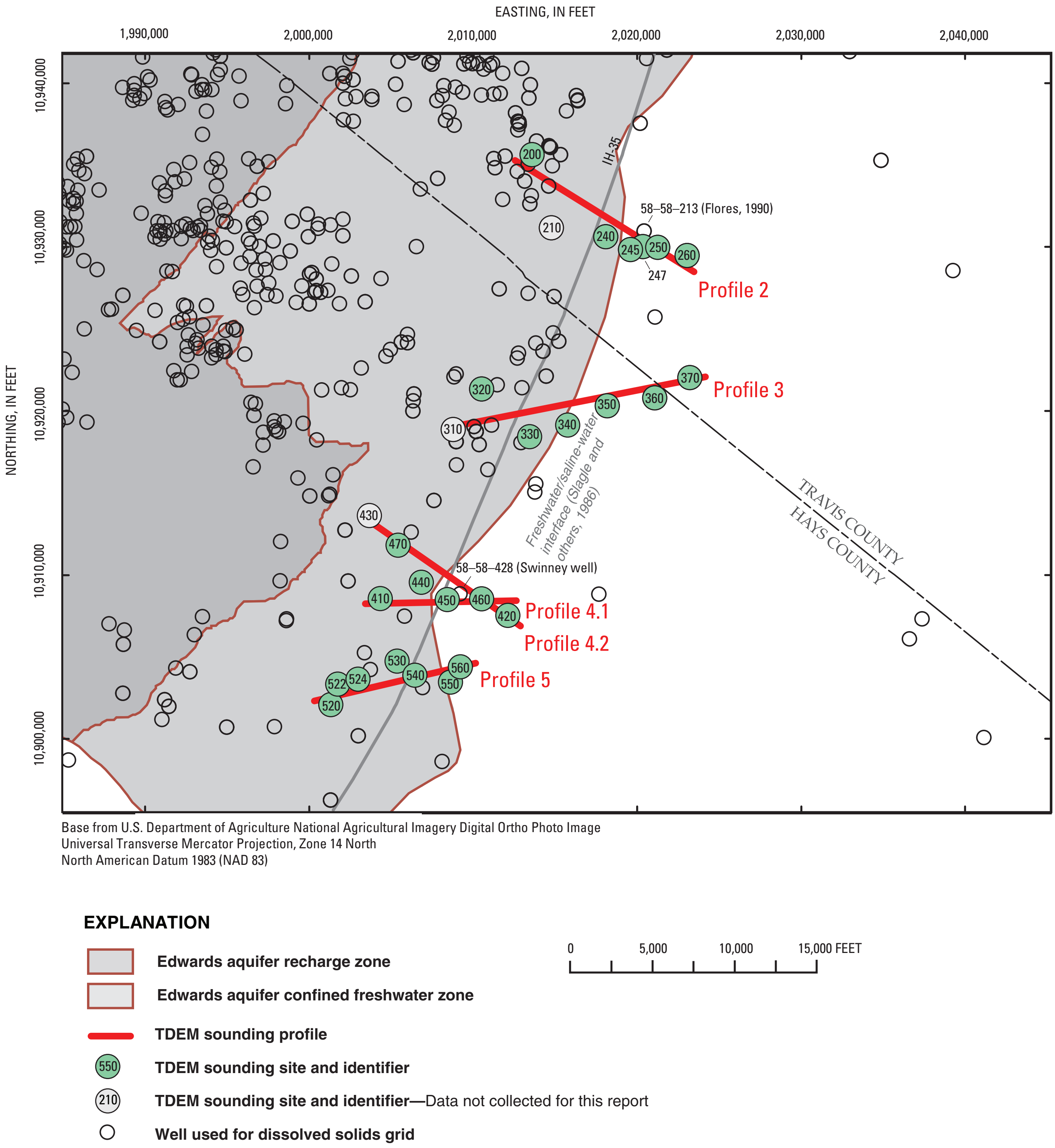


Figure 2. Locations of time-domain electromagnetic (TDEM) sounding sites and wells, Barton Springs segment of the Edwards aquifer, Travis and Hays Counties, Texas.

Description of the Barton Springs Segment of the Edwards Aquifer, Confining Units, and Study Area

The Barton Springs segment of the Edwards aquifer comprises carbonate rocks, primarily faulted and fractured limestone. The aquifer is bounded on the north by the Colorado River; on the south by a ground-water divide; on the west by the Trinity aquifer; and on the east by the saline zone (fig. 1). The aquifer crops out and is unconfined on the western side (recharge zone) and dips to the east and becomes more deeply buried and confined with distance toward the saline zone.

The rocks of the aquifer consist of the Edwards Group and the Georgetown Formation of Lower Cretaceous age (Maclay, 1995; Small and others, 1996) (table 2). Where confined above, the upper confining unit comprises (from oldest to youngest) the Del Rio Clay, Buda Limestone, Eagle Ford Group, Austin Group, Taylor Group, and Navarro Group (Barker and Ardis, 1996, plate 1) of Upper Cretaceous age. The lower confining unit consists of the generally less permeable (than the Edwards Group) Glen Rose Limestone of the Trinity aquifer.

Recharge to the aquifer occurs primarily by downward leakage through the beds of major streams that cross the recharge zone from west to east (Slade and others, 1986). Barton Springs on Barton Creek near the Colorado River (fig. 1) is the primary natural discharge point of the aquifer. Solution-enhanced karst features (fractures, faults, sinkholes) enhance the transmissivity of the aquifer, probably more so in the freshwater zone than in the saline zone. Rocks of the freshwater zone are thought to be relatively more transmissive than rocks of the saline zone (Flores, 1990; Maclay, 1995).

Water in the freshwater zone of the aquifer generally is a calcium-bicarbonate to calcium-magnesium-bicarbonate type that contains less than 500 mg/L DS concentration (Senger and Kreitler, 1984) (although for this report, freshwater is defined as water containing less than 1,000 mg/L DS concentration). Sodium and chloride are the dominant ions of water in the saline zone, which has DS concentration greater than 1,000 mg/L.

The study area overlies the transition zone where the northwest-to-southeast Travis County-Hays County line passes through near Buda (fig. 1). Land cover east of Interstate Highway 35 (IH–35) primarily is rural open ranchland, and land cover west of IH–35 largely is commercial and urban. Depth from land surface to the top of the aquifer in the study area ranges from negligible to about 800 ft.

Acknowledgments

The authors acknowledge and extend appreciation to Joe Beery and Guy Rials, BSEACD, for their assistance during data collection. Thanks also are extended to all landowners

Table 2. Correlation between hydrogeologic and stratigraphic units associated with the Barton Springs segment of the Edwards aquifer, Travis and Hays Counties, Texas.

[Stratigraphic units modified from Barker and Ardis (1996, pl. 1); Small and others (1996, table 1)]

<table>
<tr><th>Series</th><th>Hydrogeologic unit</th><th colspan="3">Stratigraphic unit</th></tr>
<tr><td rowspan="6">Upper Cretaceous</td><td rowspan="6">Upper confining unit</td><td colspan="3">Navarro Group</td></tr>
<tr><td colspan="3">Taylor Group</td></tr>
<tr><td colspan="3">Austin Group</td></tr>
<tr><td colspan="3">Eagle Ford Group</td></tr>
<tr><td colspan="3">Buda Limestone</td></tr>
<tr><td colspan="3">Del Rio Clay</td></tr>
<tr><td rowspan="9">Lower Cretaceous</td><td rowspan="8">Edwards aquifer, Barton Springs segment</td><td colspan="3">Georgetown Formation</td></tr>
<tr><td rowspan="7">Edwards Group</td><td rowspan="3">Person Formation</td><td>Cyclic and marine members, undivided</td></tr>
<tr><td>Leached and collapsed members, undivided</td></tr>
<tr><td>Regional dense member</td></tr>
<tr><td rowspan="4">Kainer Formation</td><td>Grainstone member</td></tr>
<tr><td>Kirschberg evaporite member</td></tr>
<tr><td>Dolomite member</td></tr>
<tr><td>Basal nodular member</td></tr>
<tr><td>Lower confining unit (Trinity aquifer)</td><td colspan="3">Glen Rose Limestone</td></tr>
</table>

for permission to access to their properties; especially to Kathleen Adkins and Ken Rutlidge, Adkins Ranch; Don Killibrew, Texas Lehigh Cement Co.; Steve Bartlett, Sunfield Municipal Utility District No. 2; and Donald and Douglas Dacy.

Methods and Assessment of Data

Geodatabase Development

Geodatabases are spatial extensions of tabular data that allow users to correlate numerical data with physical and spatial components. With geodatabases, geographic data can be manipulated to represent the real world using a geographic information system (GIS) to produce maps, interactive queries, and various types of spatial analyses in one integrated environment. For this study, Oasis montaj (Geosoft, Inc., 2006) was the software used to compile geologic, lithologic, geochemical, and TDEM geophysical data. The TDEM data imported into Oasis montaj are "smooth" models (vertical delineations of estimated true resistivity) generated for each sounding. The software typically is used to create two- and three-dimensional sections of subsurface electrical stratigraphy. Two-dimensional sections were created for this report.

A site map comprising roads, urban areas, and all 25 sounding sites was imported into the geodatabase. Additional data were imported with information to facilitate analysis of the collected TDEM data. A table of DS concentrations obtained from wells in the study area (appendix 1) were used to generate an areal grid of concentrations from which the approximate lateral location of the freshwater/saline-water transition zone could be identified (fig. 3). The grid was used as a reconnaissance guide to locate sounding sites across the transition zone. Geologic (stratigraphic unit) and hydrogeologic (aquifer and confining unit) contact data from geologic sections constructed from existing data along each TDEM profile also were input to the geodatabase to associate with TDEM measurements.

Geologic Sections

Geologic sections (figs. 4, 5) were constructed so that TDEM resistivity data could be associated with hydrogeologic and stratigraphic units. Subsurface geologic data in the BSCEAD database (Barton Springs/Edwards Aquifer Conservation District, written commun., 2006), primarily from geophysical and drillers' logs, test holes, and water wells, were used to construct geologic sections. Geologic control points are sparse east of IH–35; therefore there is less confidence in the sections in the easternmost part of the study area. In a few cases, the depth of the casing was interpreted to be the top of the aquifer, as most drillers install casing through the incompetent Del Rio Clay, completing the casing in the upper part of the Georgetown Formation. Within the Edwards aquifer and shown in the sections of figure 5 is the regional dense member, a poorly permeable, dense, carbonate mudstone that is recognizable in test hole cores by its lithology and on geophysical logs by distinct shifts in log traces (Maclay, 1995).

Site Selection

Twenty-five sounding sites were selected to provide a uniform distribution of data to determine variations in electrical properties across the study area. A grid was generated from existing water-quality data-collection sites using kriging (Geosoft Inc., 2006) to aid in selecting sounding sites where DS concentrations transition from freshwater to saline water in the study area (fig. 3). Kriging interpolates values (DS concentrations in this application) from measured values at known locations (appendix 1). TDEM sounding sites were chosen to avoid urban features and where land was accessible. Urban features hinder data collection because of electromagnetic noise from sources such as power lines and underground pipelines. Initial sites along each profile were selected and sounding data collected. After preliminary data processing, additional sounding sites were sought to fill data gaps; however, in some cases desired sites could not be accessed because landowner permission could not be obtained.

Time-Domain Electromagnetic Sounding

TDEM sounding can be used to identify variations in the electrical resistivity of the subsurface, which can be linked to changes in the physical and chemical properties of soil, rock, and pore fluids. The resistivity of soils and rocks are controlled by mineralogy, clay content, water content, salinity, metallic minerals, and porosity. Changes in the resistivity of soils and rocks, either vertically or horizontally, produce variations in the electromagnetic signature measured by geophysical tools. Changes in the resistivity can be correlated to variations in the composition and physical properties of the subsurface geology, to the level that differences in lithology or rock type are accompanied by variations in resistivity (U.S. Army Corps of Engineers, 1995). However, to efficiently distinguish these differences, the geologic characteristic to be defined must have properties considerably different from background conditions (American Society for Testing and Materials, 1999). Typically, clay and shale are less resistive than sand and gravel, which in some cases can provide contrasts that could be noticeable with TDEM methods (U.S. Army Corps of Engineers, 1995).

Electromagnetic measurements are made by transmitting an alternating current into a square loop of insulated wire deployed on the land surface. The current consists of equal periods of time-on and time-off base frequencies that ranged in this application from 285 to 3 hertz (Hz), which produces an electromagnetic field near the loop. Termination of the current

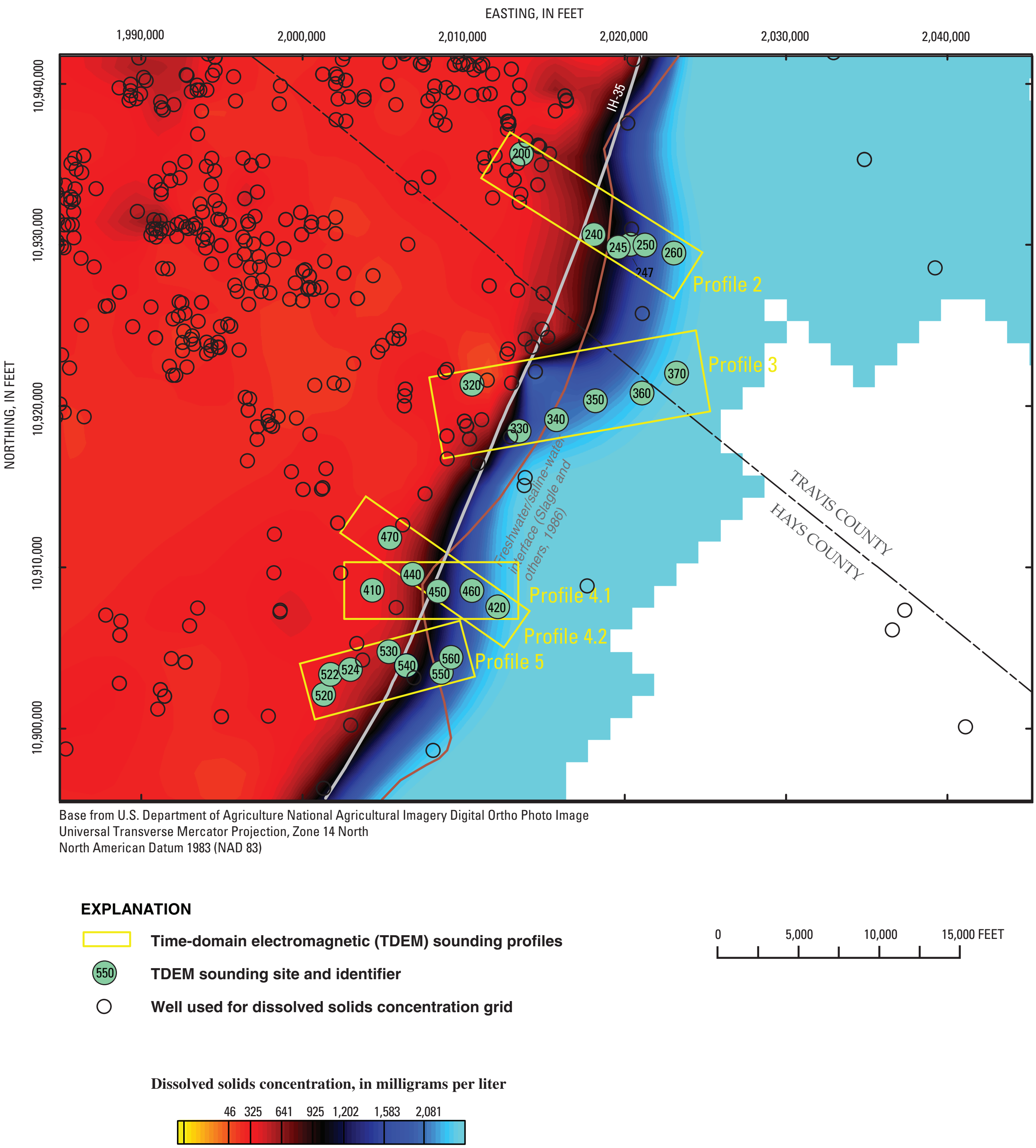


Figure 3. Location of freshwater/saline-water transition zone, Barton Springs segment of the Edwards aquifer, Travis and Hays Counties, Texas.

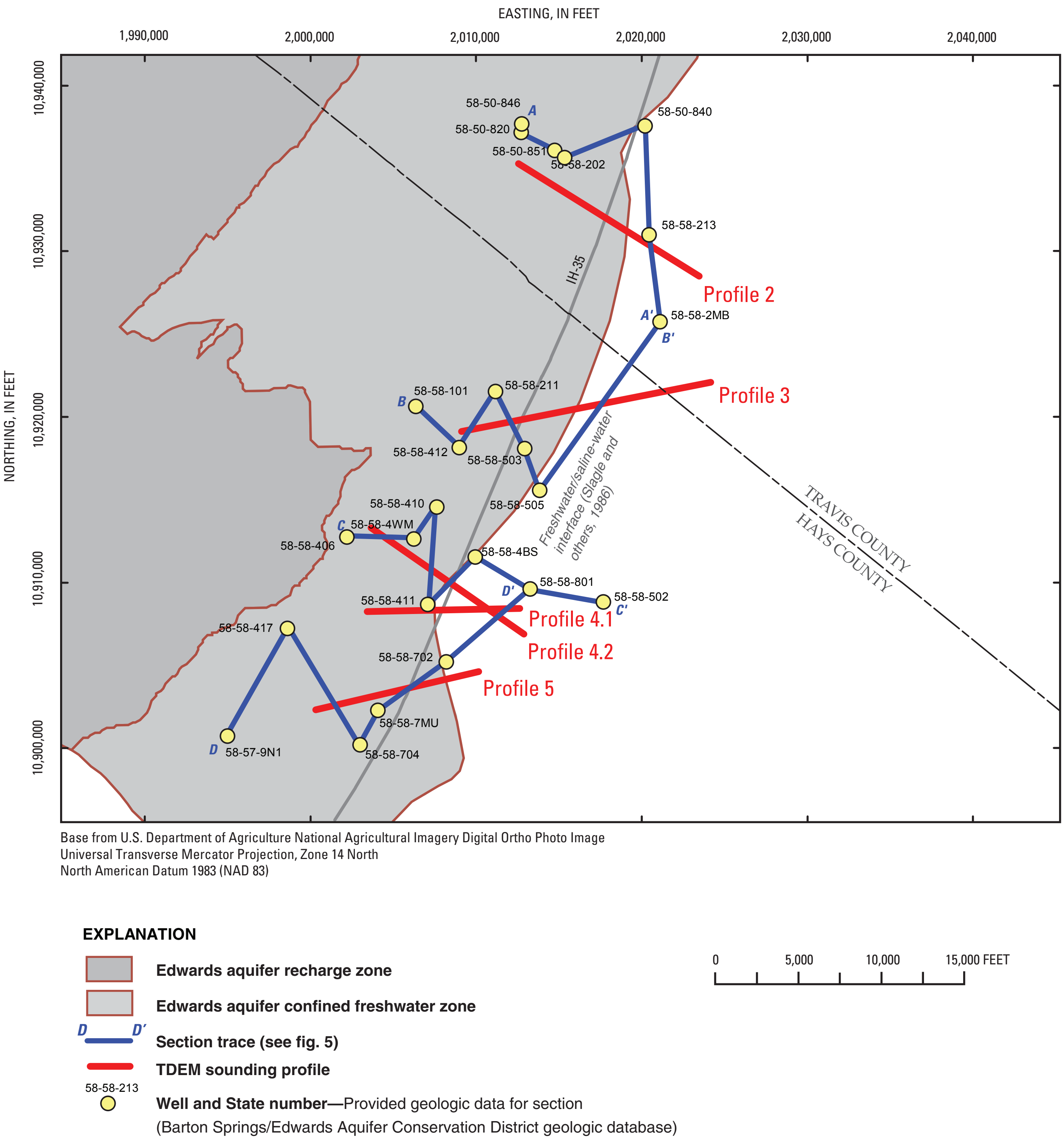


Figure 4. Locations of geologic sections and time-domain electromagnetic (TDEM) sounding profiles, Barton Springs segment of the Edwards aquifer, Travis and Hays Counties, Texas.

flow is not instantaneous, but occurs over a few microseconds, known as the ramp time, during which the magnetic field is time-variant. The time-variant nature of the induced electromagnetic field creates a secondary electromagnetic field in the ground underneath the loop in accordance with Faraday’s Law (Halliday and Resnick, 1974). This resultant field instantly begins to decay, in the process generating additional eddy currents that spread downward and outward into the subsurface like a succession of smoke rings (North Carolina Division of Water Resources, 2006). Measurements of the eddy currents are made throughout the time-off period by a receiver positioned in the center of the transmitter loop. Depth of exploration depends on the time interval after shutoff of the current, because at later times, the receiver is measuring eddy currents at increasingly greater depths. The magnitude of the eddy current voltage at specific times and depths is determined by the overall conductivity of subsurface rock units and fluids (Stewart and Gay, 1986). From this voltage measurement, the apparent resistivity can be calculated.

Transmitter loop, or antenna, selection was critical because of relatively large depths to and into the Edwards aquifer in the eastern part of the study area. Data from square-shaped transmitter loops of three sizes, 164 by 164 ft (50 meter [m]), 328 by 328 ft (100 m), and 492 by 492 ft (150 m), were examined for data quality at depth. A larger loop size increases the depth of exploration but increases resistance of the loop wire, which therefore decreases the current. For example, a 492-ft (150-m) loop transmits only 8 amps because of the added resistance of the wire, whereas a 328-ft (100-m) loop will transmit between 12 and 14 amps. Reduced current in the loop decreases the electromagnetic field strength, which decreases the reliability of data from relatively deep zones. It was determined that the 164-ft (50-m) loop was not large enough to generate reliable data at the depths needed for most of the survey. The judgment was made not to use sounding data from depths greater than 656 ft (200 m) for interpretations because of the probable lack of reliability of data from those depths.

Geonics Protem 47 (fig. 6A) and 57 (fig. 6B) systems with 492-ft (150-m) and 328-ft (100-m) transmitter-loop sizes were used to collect the TDEM soundings. The Protem 47 and 57 use a multi-turn coil to measure electromagnetic fields in the center of the transmitter loop. The Protem 47 receiver coil has an effective area of 338 square feet (31.4 square meters), and the Protem 57 receiver has an effective area of 1,076 square feet (100 square meters). The Protem 47 produced currents of 2.2–2.7 amps (depending on the size of the loop used), and the Protem 57 produced currents of 8–21 amps. The Protem 47 and 57 each have preset frequencies or repetition rates. The Protem 47 uses repetition rates of 285 Hz (ultra-high), 75 Hz (very high), and 30 Hz (high) (Geonics Limited, 2006a). The Protem 57 uses slower repetition rates of 30 Hz (high), 7.5 Hz (medium), and 3 Hz (low) (Geonics Limited, 2006b). At each sounding an integration time of 60 seconds was used to measure five different datasets or duty cycles. The five duty cycles are individual datasets that are later averaged before inverse modeling. Averaging is done to ensure data quality and repeatability. The 60-second integration time was selected after comparison with data collected with 30-second integration times. The larger integration time increased late-time data quality, which increased data quality at depth.

A Trimble 5800 dual frequency kinematic global positioning system (GPS) unit was set up at each sounding to obtain the precise location of the transmitter. Each sounding was configured from west to east using a compass, with the transmitter at the west corner, so that the receiver location in the center of the loop could be computed using the Pythagorean theorem. From the position of the transmitter, the receiver position was computed as one-half the diagonal distance of the square loop due east.

Borehole Geophysics

Borehole geophysical methods typically are used to measure and analyze the physical properties of the subsurface in wells. Geophysical probes that measure various properties are lowered into the borehole to collect data that can be displayed graphically with depth as a geophysical log. Typically, several different logs are collected because more can be observed in the analysis of a suite of logs than by analyzing single logs alone. Borehole logs offer a means to accurately estimate the thickness and physical properties of the diverse materials penetrated by a well (Keys, 1990).

The top of the Edwards aquifer is identified on a borehole geophysical log from a previous study in the area (Flores, 1990) (fig. 2) by the increase in gamma-ray activity across the Georgetown Formation/Del Rio Clay contact (fig. 7), likely caused by higher clay content in the Del Rio Clay. Also prominent on the geophysical log above the Del Rio Clay are increases in gamma-ray activity that Flores (1990) interpreted as marking the Eagle Ford Group and the Navarro and Taylor Groups (undifferentiated). These units also likely have relatively high clay content. It is these clayey units, which are relatively conductive like saline water, that were of concern at the outset of the study regarding their potential to adversely affect TDEM measurements indicating saline water in the aquifer.

Geophysical borehole logs were collected at State well 58–58–428 (Swinney well) in Hays County (fig. 2; appendix 2) for comparison with the Flores (1990) log and to better determine the electrical stratigraphy of the site. Gamma, resistivity, temperature, and specific conductance logs were collected. The gamma log indicates variations in lithology similar to those of the Flores (1990) gamma log. The same relatively clayey units are apparent on both logs.

Data Processing and Quality

The dual frequency kinematic GPS data were processed through the Online Positioning User Service (OPUS) (National Geodetic Survey, 2006) 1 week after collection to

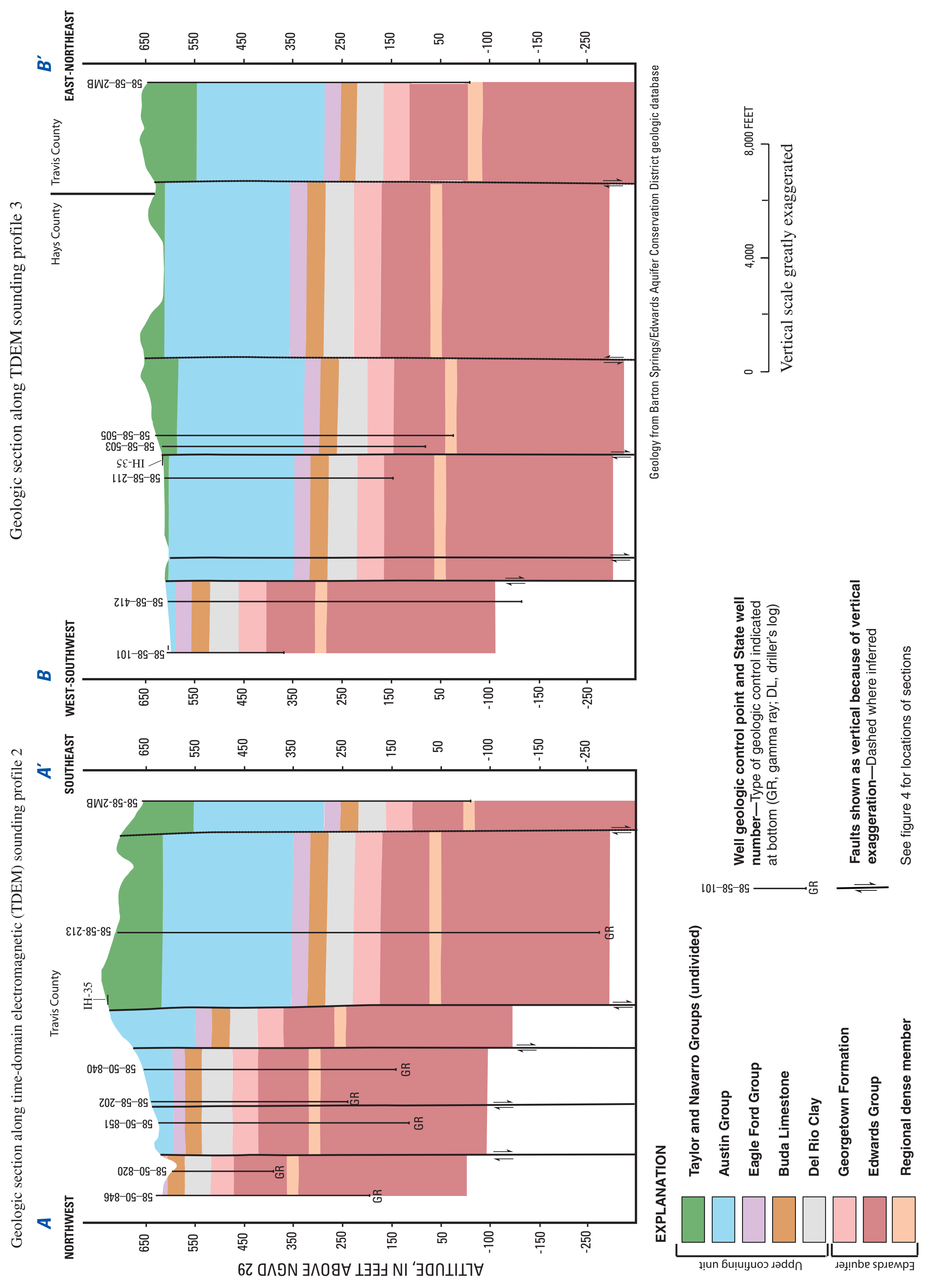


Figure 5. Geologic sections of the Barton Springs segment of the Edwards aquifer, Travis and Hays Counties, Texas.

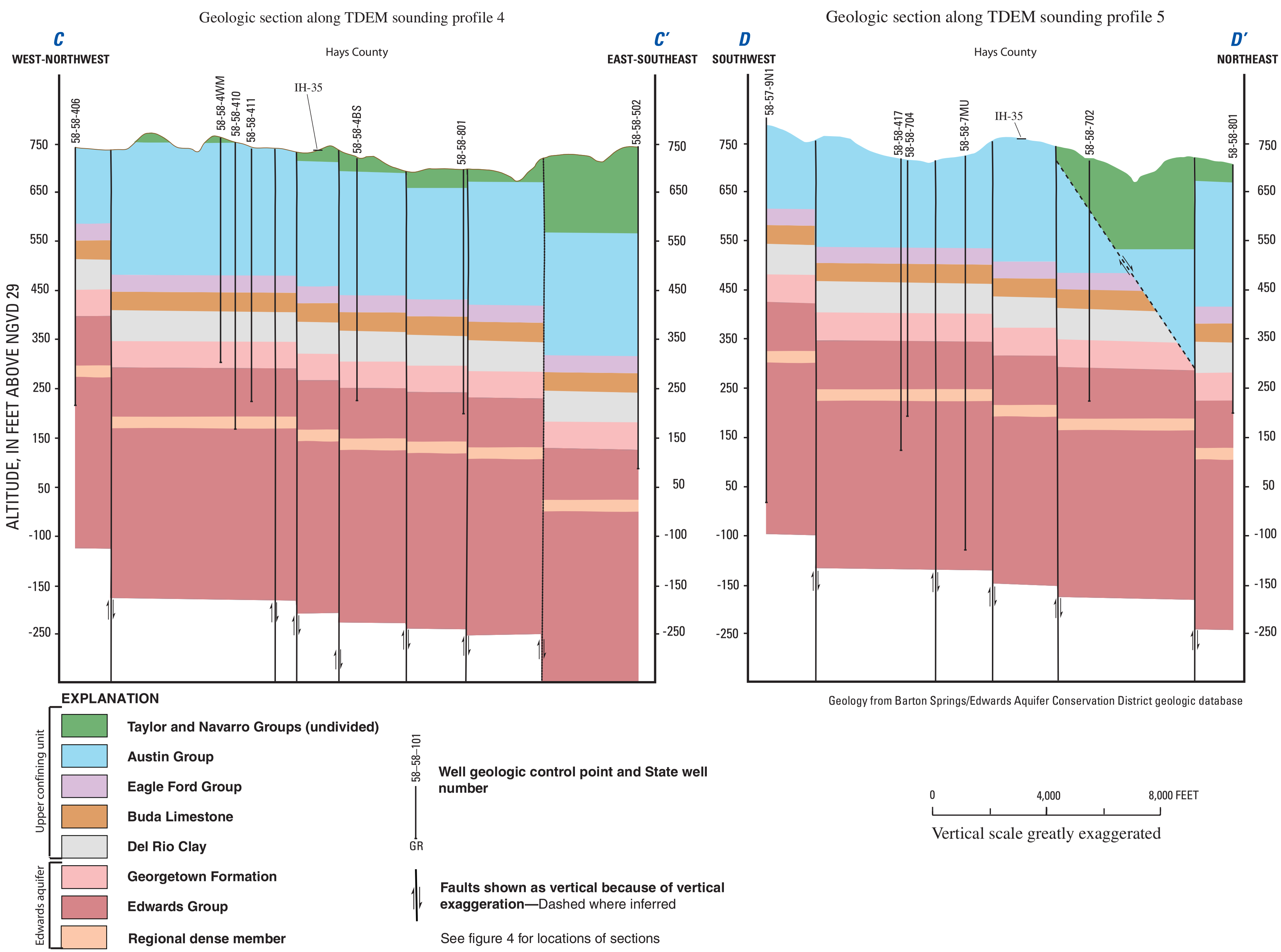


Figure 5. Continued.

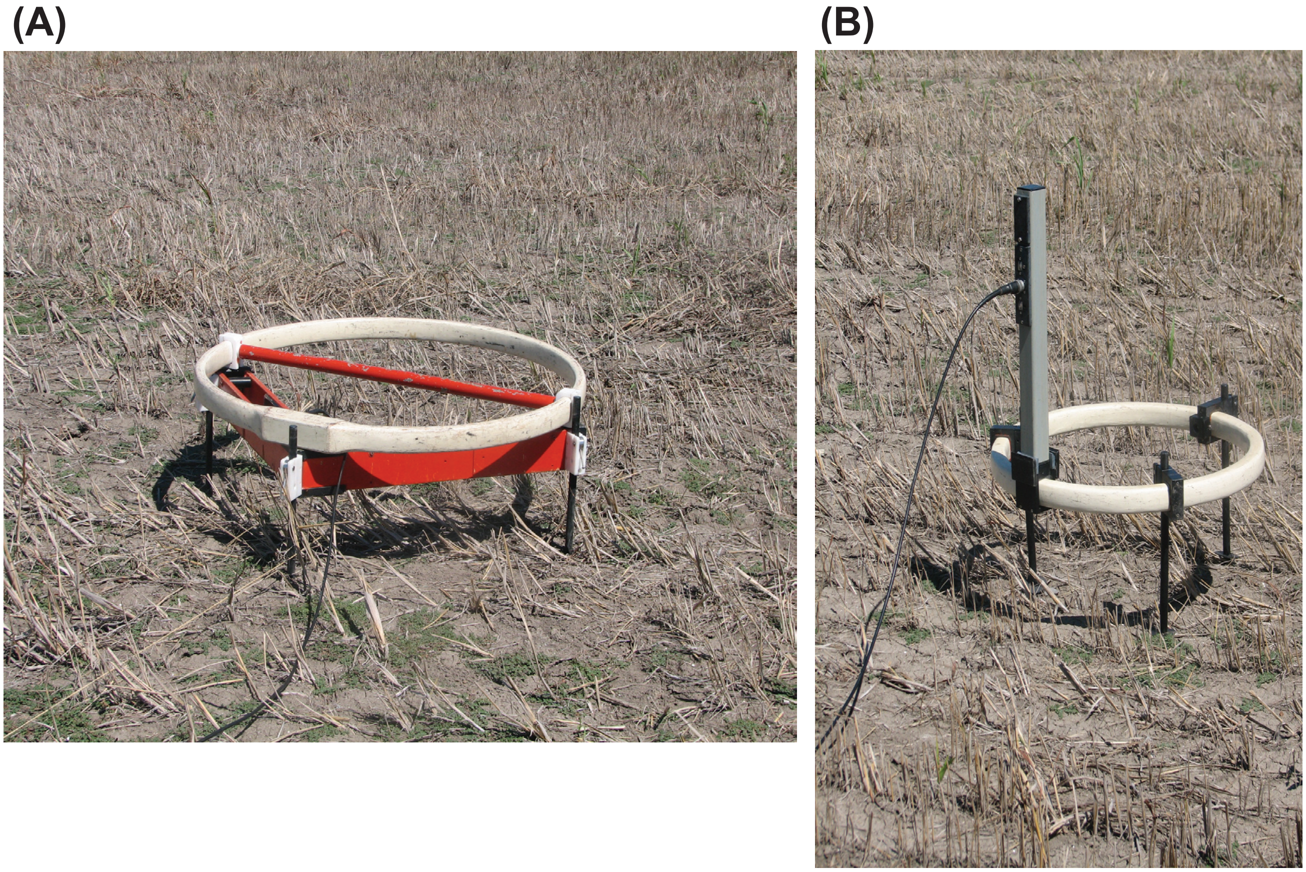


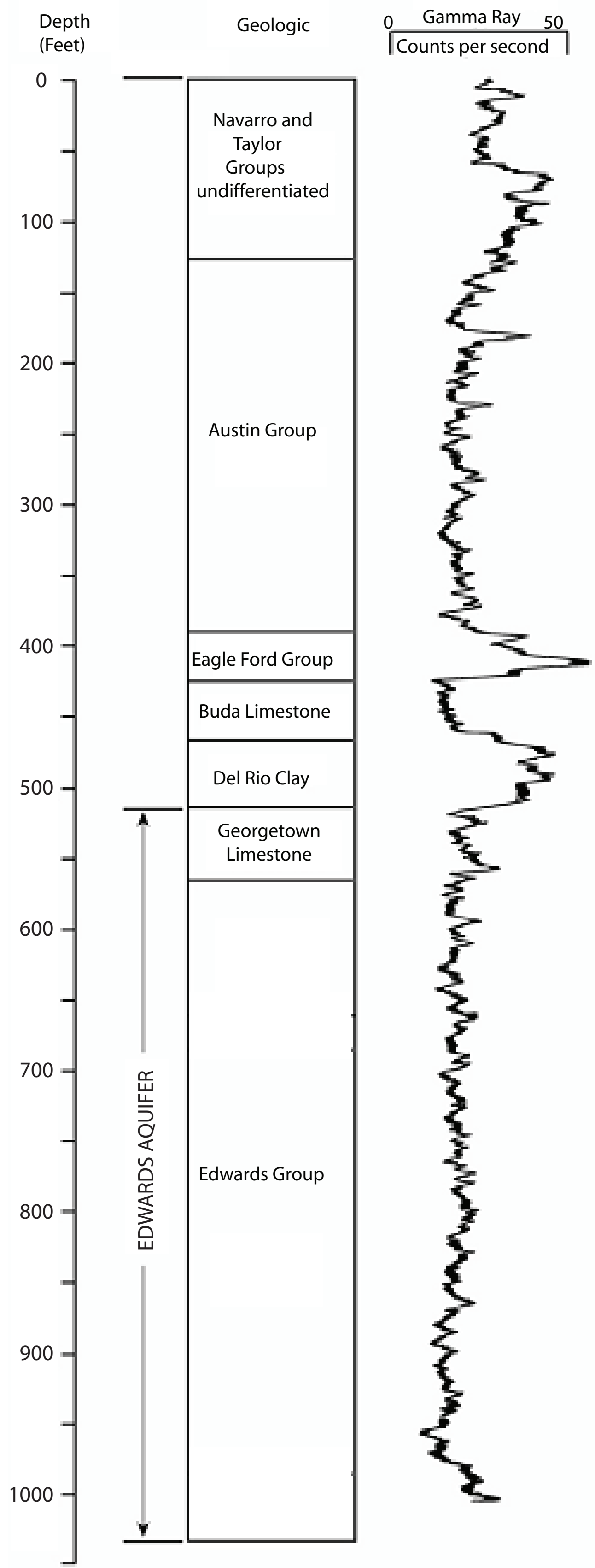
Figure 6. Receiver coil for Geonics (A) Protem 47 and (B) Protem 57.

ensure accuracy of sounding locations. There are three different levels of OPUS solutions: ultra-rapid, rapid, and precise. Ultra-rapid solutions are collected in near real-time and are processed using a predicted satellite orbit. Rapid solutions are processed within 1 day of collection and use a partially predicted orbit; and precise solutions are calculated after 3 days and use the exact orbit. OPUS suggests collecting GPS data for a minimum of 2 hours for best results. For this survey, GPS data were collected for about 30 minutes at each site; highly accurate locations were not critical for this survey. The GPS solutions are in appendix 3.

For each sounding, the voltage data were averaged and evaluated statistically. The raw field voltage data were checked first for uncertainty by computing the standard deviation of the data. In some cases, the voltages were negative at the late-time gates, so the absolute values for those voltages were used to evaluate the data statistically. The negative data then were deleted before any other processing was done. The raw voltage data were averaged over the five duty cycles for each gate for each frequency using TEM2IX1D (Interpex Limited, 1996). TEM2IX1D is a program used to analyze and average the duty cycles for each sounding. Voltages with standard deviation greater than 3 percent were deleted before modeling, which eliminated data from late-time gates that yielded the lowest signal-to-noise ratio. The computed standard deviations of the voltages are in appendix 4.

Inverse Modeling

Apparent resistivity, as calculated from field measurements of voltage, is the resistivity of an equivalent electrically homogeneous and isotropic subsurface (Grant and West, 1965). Inverse modeling is the process of creating an estimate of the true distribution of subsurface resistivity (which reflects heterogeneous, anisotropic rocks) from the measured apparent resistivity obtained from TDEM soundings (which reflects homogeneous, isotropic rocks). IX1D, a program developed by Interpex Limited (1996), was used for inverse modeling. The measured apparent resistivity data were graphed as a function of time on a linear scale (appendix 5). Data points that deviated severely (a judgment decision) from the curve were deleted before inverse modeling. A smooth model consisting of 100 layers with a minimum depth of 3.281 ft (1 m), a maximum depth of 2,296 ft (700 m), and a starting resistivity of 10 ohm-meters (ohm-m) was used to approximate the measured resistivity points. A smooth model is a vertical delineation of calculated apparent resistivity that represents a (non-unique)



Modified from Flores, 1990, appendix 2

Figure 7. Geologic and gamma-ray geophysical logs, test well 58–58–213, Travis County, Texas.

estimate of the true resistivity. Ridge regression (Interpex Limited, 1996) was used by the inversion software in a series of iterations to create a smooth model for each sounding site. Iterations were continued until the root mean square (RMS) error between measured and calculated apparent resistivity was less than 0.1 percent between iterations. Graphs of the smooth models for the 25 sounding sites are in appendix 5. The entire datasets of raw and processed TDEM data are in appendix 6.

RMS errors between measured and calculated apparent resistivity for the soundings range from 1.71 to 8.72 percent (table 3). After each sounding was inverted in IX1D, the one-dimensional smooth model for the sounding was imported into the geodatabase to compare with models from other soundings along the same profile. The TDEM smooth models were superimposed on the geologic sections.

Delineation of Transition Zone Using Time-Domain Electromagnetic Soundings

The effectiveness of using TDEM soundings to delineate the transition zone is indicated by comparing the distribution of resistivity in the aquifer with the distribution of DS concentrations in the aquifer along profiles 2–5, as shown in figures 8–12. (Profile 1 was abandoned because of a lack of landowner permissions to access the necessary sites.) TDEM sounding data show that, in general, the Edwards aquifer in the study area is characterized by a sharp change in resistivity from west to east. The western part of the Edwards aquifer in the study area shows higher resistivity than the eastern part. The higher resistivity regions correspond to lower DS concentrations (freshwater), and the lower resistivity regions correspond to higher DS concentrations (saline water). Resistivities from soundings along each profile relative to known DS concentrations are discussed below.

Profile 2

Profile 2 (fig. 3) comprises six TDEM soundings (fig. 8). Sounding 200 on the far west end of the profile depicts a continuous vertical decrease in resistivity (fig. 8B, C) that is interpreted as indication of an increase in DS concentration with depth. More-saline water apparently occurs in the lower part of the aquifer at the site. Sounding 240 also indicates a vertical decrease in resistivity (fresher water overlying more-saline water), but the decrease is attenuated compared to that of sounding 200. Soundings 245, 247, 250, and 260 generally show decreasing resistivity with distance to the east, which is interpreted as increasing salinity in the aquifer with distance to the east. Comparison of the lateral location of the interpreted freshwater/saline-water interface based on resistivity with the location based on DS concentrations (fig. 8A) shows general agreement (approximately between soundings 240 and 245).

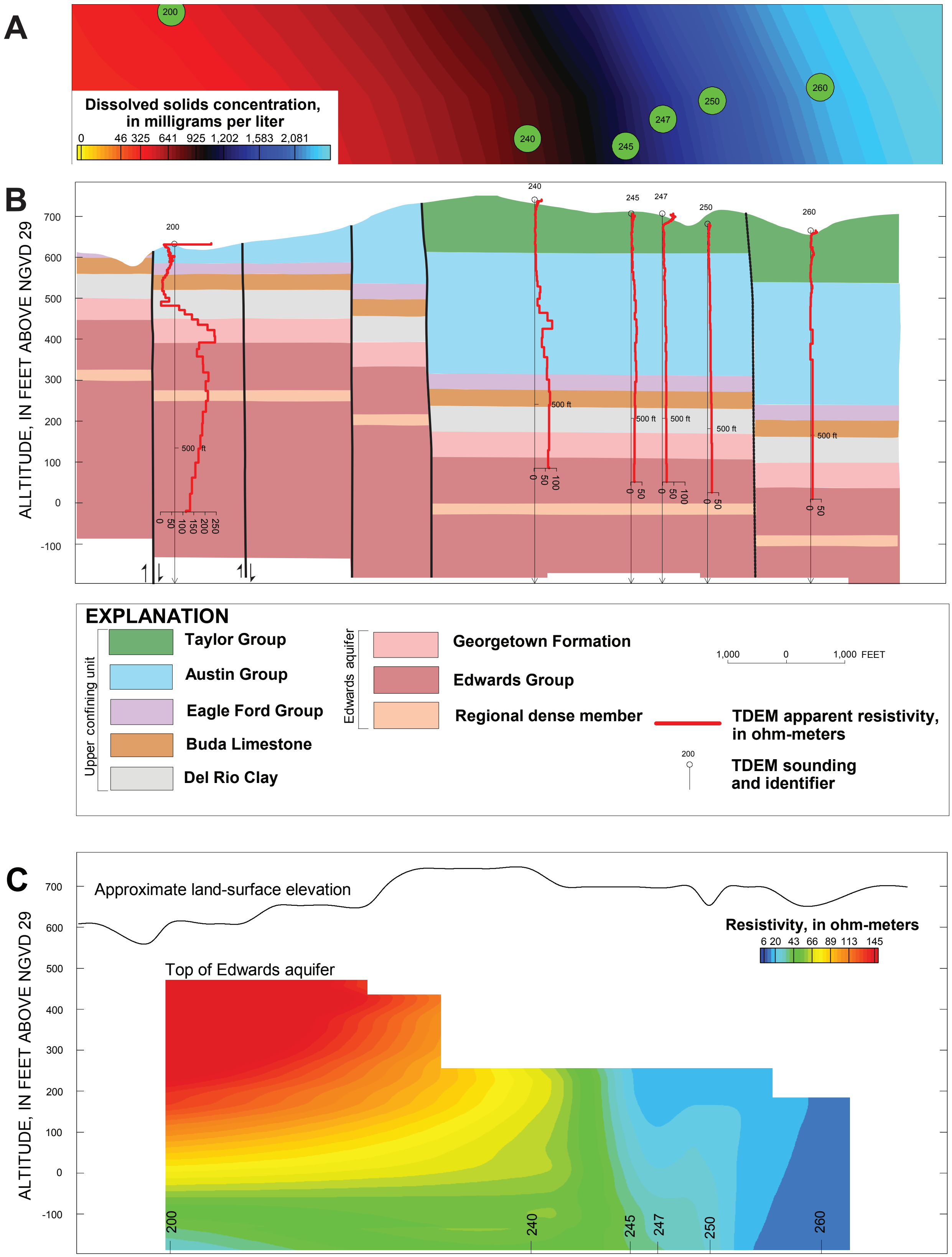


Figure 8. Profile 2, Barton Springs segment of the Edwards aquifer, Travis and Hays Counties, Texas (A) plan view of distribution of dissolved solids concentrations from previously collected data, (B) nearby geologic section interpreted from previously collected data and overlain by smooth inversion models of resistivity at each sounding, and (C) resistivity section from time-domain electromagnetic (TDEM) soundings.

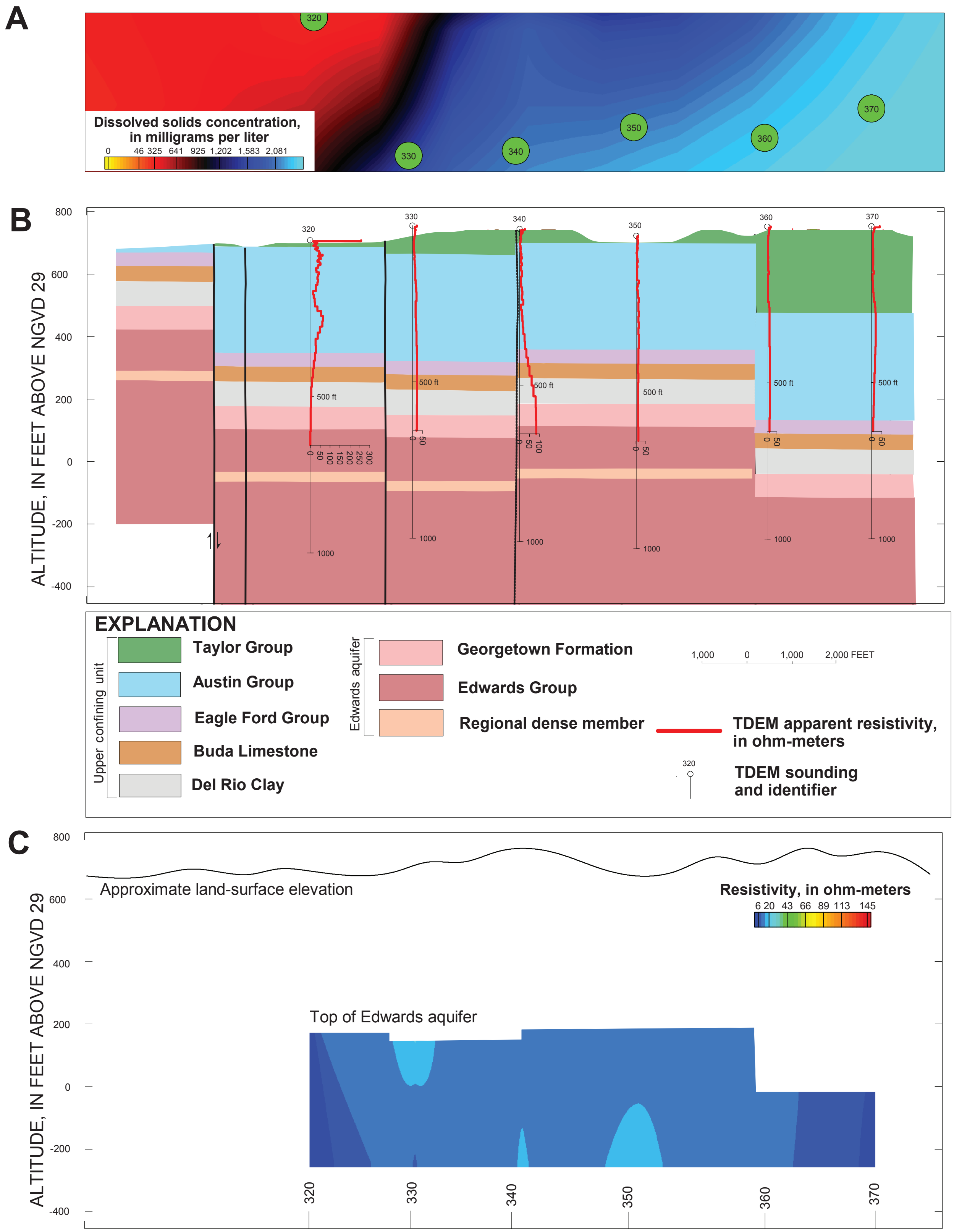


Figure 9. Profile 3, Barton Springs segment of the Edwards aquifer, Travis and Hays Counties, Texas (A) plan view of distribution of dissolved solids concentrations from previously collected data, (B) nearby geologic section interpreted from previously collected data and overlain by smooth inversion models of resistivity at each sounding, and (C) resistivity section from time-domain electromagnetic (TDEM) soundings.

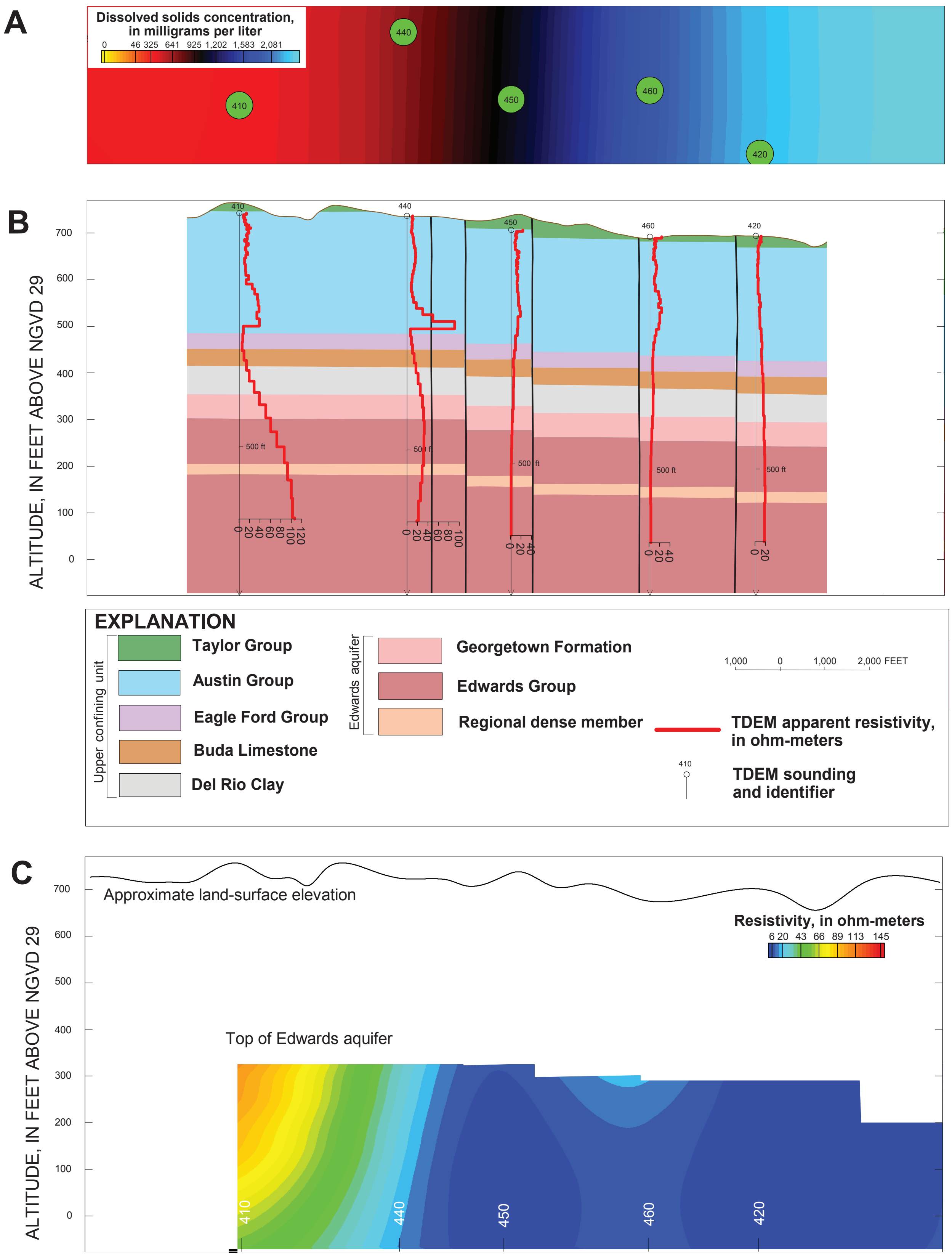


Figure 10. Profile 4.1, Barton Springs segment of the Edwards aquifer, Travis and Hays Counties, Texas (A) plan view of distribution of dissolved solids concentrations from previously collected data, (B) nearby geologic section interpreted from previously collected data and overlain by smooth inversion models of resistivity at each sounding, and (C) resistivity section from time-domain electromagnetic (TDEM) soundings.

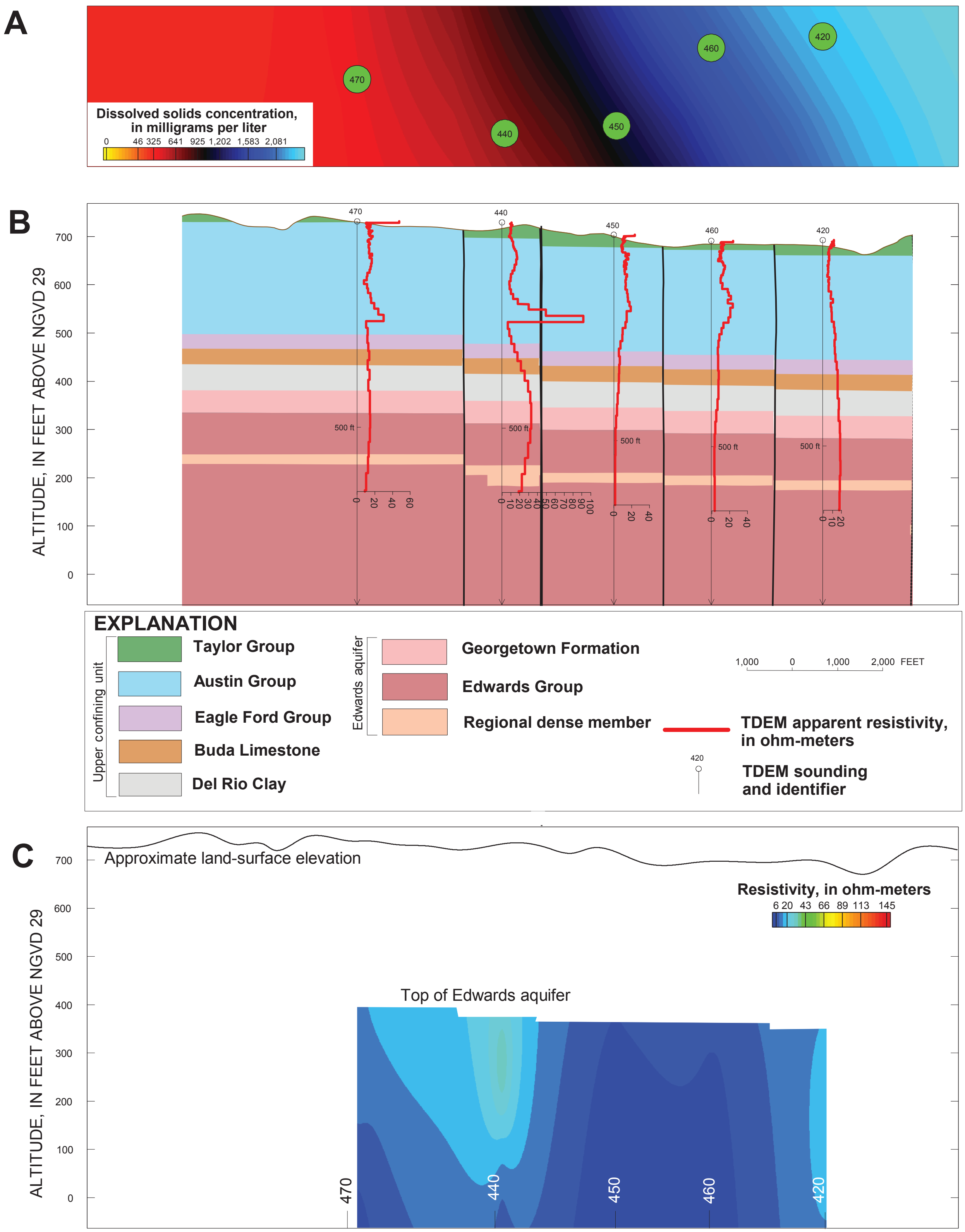


Figure 11. Profile 4.2, Barton Springs segment of the Edwards aquifer, Travis and Hays Counties, Texas (A) plan view of distribution of dissolved solids concentrations from previously collected data, (B) nearby geologic section interpreted from previously collected data and overlain by smooth inversion models of resistivity at each sounding, and (C) resistivity section from time-domain electromagnetic (TDEM) soundings.

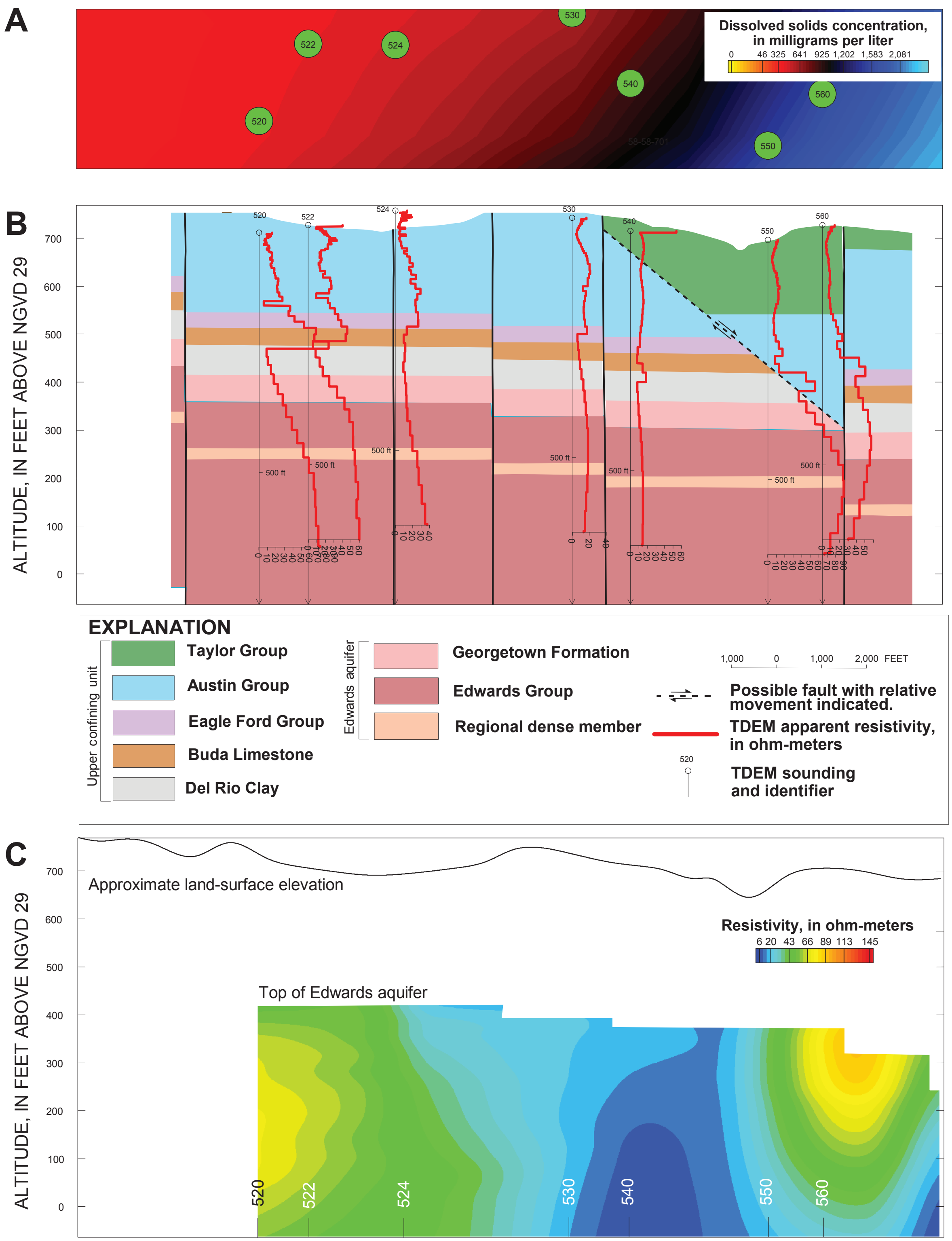


Figure 12. Profile 5, Barton Springs segment of the Edwards aquifer, Travis and Hays Counties, Texas (A) plan view of distribution of dissolved solids concentrations from previously collected data, (B) nearby geologic section interpreted from previously collected data and overlain by smooth inversion models of resistivity at each sounding, and (C) resistivity section from time-domain electromagnetic (TDEM) soundings.

Table 3. Root mean square (RMS) error between measured and calculated apparent resistivity for soundings, Barton Springs segment of the Edwards aquifer, Travis and Hays Counties, Texas.

Profile 2		Profile 3		Profiles 4.1, 4.2		Profile 5	
Sounding	RMS error (percent)	Sounding	RMS error (percent)	Sounding	RMS error (percent)	Sounding	RMS error (percent)
200	3.88	320	3.63	410	4.25	520	3.48
240	5.47	330	2.64	420	1.88	522	2.53
245	5.4	340	2.49	440	1.71	524	2.66
247	2.27	350	2.55	450	2.73	530	1.78
250	2.79	360	3.76	460	3.91	540	6.04
260	8.55	370	3.22	470	4.33	550	7.65
						560	8.72

Profile 3

Profile 3 (fig. 3) comprises six TDEM soundings (fig. 9), only four of which penetrate the upper part of the aquifer within the estimated range of reliability (656 ft [200 m]). Sounding 320 on the far west end of the profile shows very low resistivity (about 4 ohm-m [appendix 5, fig. 5.7) in the Edwards aquifer (fig. 9B, C) that would indicate saline water. This response might be influenced by noise caused by urban features, as the sounding was collected about 330 ft (100 m) west of a large commercial building. The sounding was collected there because it was the only area available on what was thought to be the west side of the transition zone. Adjacent sounding 330 also indicates low resistivity (about 15 ohm-m [appendix 5, fig. 5.8]) that is in a range indicative of saline water. Similarly, soundings 340 and 350 indicate lower resistivity (appendix 5, figs. 5.9, 5.10) indicative of saline water in the upper part of the aquifer. The top of the Edwards aquifer at soundings 360 and 370 is deeper than 656 ft, thus the depth of the aquifer there exceeds the capability of the soundings to yield reliable data. The four soundings of profile 3 that penetrate the top of the aquifer indicate saline water, which in turn indicates that the transition zone is west of the westernmost sounding (320). The lateral location of the interface along the profile based on DS concentrations (fig. 9A) appears to be between soundings 320 and 330. The lack of agreement between the location of the transition zone based on resistivity and the location based on DS concentrations cannot be explained with available data.

Profile 4

Profile 4 comprises two alternate profile lines designated profiles 4.1 and 4.2 (fig. 3). Each of these contains five soundings (figs. 10, 11). The two profiles are the same except that the westernmost sounding is 410 in profile 4.1 and 470 in profile 4.2. Two profiles were done because of the relatively large north-south distance between soundings 410 and 470, necessitated by lack of permission to access property. The profiles differ substantially in orientation relative to points of the compass. It is evident from both profiles that resistivity of the Edwards aquifer decreases from west to east. In profile 4.1 (fig. 10B, C), sounding 410 shows relatively high resistivity in the aquifer (about 30–100 ohm-m) (appendix 5, fig. 5.13) indicative of freshwater. Soundings 440 and 450 show progressively decreasing resistivity toward the east, and the transition to saline water appears to occur near sounding 440. Low resistivity at soundings 460 and 420 on the east end of the profile are interpreted as indicative of saline water.

In profile 4.2 (fig. 11) in which sounding 470 replaces sounding 410, the expected indication of freshwater at sounding 470 (based on relatively high resistivity at sounding 410) is missing; resistivity at sounding 470 is low and in a range indicative of saline water. This might be because of electromagnetic noise in the area—the west end of the profile was in a relatively urbanized part of the city of Buda. Although the ranges of resistivity in resistivity section 4.2 (fig. 11C) are somewhat different from those in resistivity section 4.1 (fig. 10C), the pattern of resistivity and the inferred location of the freshwater/saline-water interface (around sounding 440) are essentially the same in both sections, as would be expected. The location of the interface along the two profiles based on DS concentrations (figs. 10A, 11A) appears to be farther east, in the area of soundings 450 and 460, but not substantially different from that indicated by the sounding data.

Profile 5

Profile 5 (fig. 3) comprises seven TDEM soundings (fig. 12). Soundings 520 and 522, at the far western end of the profile, show resistivities indicative of freshwater. Moving eastward, resistivities indicate the probable location of the interface between soundings 524 and 530 (fig. 12C). At sounding 540, the resistivity clearly indicates saline water. Continuing eastward, however, relatively higher resistivities from soundings 550 and 560 indicate that the water is fresher at those sites than the water immediately to the west, an anomaly relative to what would be expected. The location of the interface in profile 5 based on DS concentrations (fig. 12A) appears to be at about sounding 524, close to the location indicated by the resistivity data. The anomalous zone of relatively high resistivity toward the eastern end of profile 5 could not be confirmed by DS concentrations because of sparse DS data in that area; however, the presence of a possible fault could have a local effect on water quality.

Evaluation of Findings

On the basis of reasonably close matches between the inferred locations of the freshwater/saline-water transition zone in the Edwards aquifer in the study area from resistivities and from DS concentrations in three of the four profiles, TDEM sounding appears to be a suitable tool for delineating the transition zone. The fact that the Edwards aquifer lies about 200–500 ft below land surface in the area of the transition zone did not appear to adversely affect TDEM measurements. The ability to identify the transition zone from TDEM measurements was not hindered by the presence of relatively low-resistivity/high-conductivity lithologic units (Del Rio Clay, Eagle Ford Group, and Navarro and Taylor Groups [undifferentiated]) in the upper confining unit of the aquifer. Few sounding sites were near enough to urban features for the data to potentially have been affected. However, urban features might have adversely affected data from two of the 25 soundings (soundings 320 and 470). Whether urban features adversely affected the sounding data could not be determined. Judicious site selection to avoid urban features to the extent possible is necessary in future TDEM applications in the Barton Springs segment of the Edwards aquifer.

Summary and Conclusions

During September 2006, the USGS, in cooperation with the Barton Springs/Edwards Aquifer Conservation District, conducted a geophysical pilot study to determine whether time-domain electromagnetic (TDEM) sounding could be used to delineate the freshwater/saline-water transition zone in the Barton Springs segment of the Edwards aquifer in Travis and Hays Counties, Texas. This application of TDEM sounding also was a test to indicate whether high-quality data could be obtained from the required depths (200–500 ft to the top of the aquifer plus a substantial thickness of the aquifer); and whether relatively low-resistivity clayey units that compose the upper confining unit of the aquifer would adversely affect investigators' ability to identify the transition zone from TDEM measurements. The pilot application of TDEM sounding also was an opportunity to test whether urban features would adversely affect the sounding data. Twenty-five TDEM soundings were made along four 2–3-mi-long profiles in a study area overlying the transition zone. The soundings yield measurements of subsurface electrical resistivity, the variations in which were correlated with hydrogeologic and stratigraphic units, and then with dissolved solids (DS) concentrations in the aquifer.

A geodatabase consisting of geologic, lithologic, geochemical, and TDEM data was developed. The geodatabase aided in the selection of sounding sites and was used to create two-dimensional sections of estimated true resistivity (electrical stratigraphy).

Geonics Protem 47 and 57 systems with 492-ft (150-m) and 328-ft (100-m) transmitter-loop sizes were used to collect the TDEM soundings (voltage data from which resistivity is calculated). For each sounding, voltage data from five collected datasets were averaged and evaluated statistically—that is, voltages with standard deviation greater than 3 percent were deleted before inverse modeling.

Inverse modeling is the process of creating an estimate of the true distribution of subsurface resistivity from the measured apparent resistivity obtained from TDEM soundings. A smooth model is a vertical delineation of calculated apparent resistivity that represents a (non-unique) estimate of the true resistivity. A smooth model for each sounding site was created using an iterative software program. Iterations were continued until the root mean square (RMS) error between measured and calculated apparent resistivity was less than 0.1 percent between iterations.

The effectiveness of using TDEM soundings to delineate the transition zone was indicated by comparing the distribution of resistivity in the aquifer with the distribution of DS concentrations in the aquifer along the profiles. TDEM sounding data show that, in general, the Edwards aquifer in the study area is characterized by a sharp change in resistivity from west to east. The western part of the Edwards aquifer in the study area shows higher resistivity than the eastern part. The higher resistivity regions correspond to lower DS concentrations (freshwater), and the lower resistivity regions correspond to higher DS concentrations (saline water).

On the basis of reasonably close matches between the inferred locations of the freshwater/saline-water transition zone in the Edwards aquifer in the study area from resistivities and from DS concentrations in three of the four profiles, TDEM sounding appears to be a suitable tool for delineating the transition zone. The fact that the Edwards aquifer lies about 200–500 ft below land surface in the area of the transition zone did not appear to adversely affect TDEM measurements. The ability to identify the transition zone from TDEM measurements was not hindered by the presence of relatively low-resistivity lithologic units in the upper confining unit of the aquifer. Whether urban features adversely affected the sounding data could not be determined. Urban features might have adversely affected data from the two soundings near enough to urban features to have been potentially affected. Judicious site selection to avoid urban features to the extent possible is called for in future TDEM applications in the Barton Springs segment of the Edwards aquifer.

References

American Society for Testing and Materials, 1999, Standard guide for selecting surface geophysical methods: ASTM International Standard D 6429.

Baker, E.T., Jr., Slade, R.M., Jr., Dorsey, M.E., Ruiz, L.M., and Duffin, G.L., 1986, Geohydrology of the Edwards aquifer in the Austin area, Texas: Texas Water Development Board Report 293, 217 p.

Barker, R.A., and Ardis, A.F., 1996, Hydrogeologic framework of the Edwards-Trinity aquifer system, west-central Texas, in Regional Aquifer-System Analysis—Edwards-Trinity aquifer system: U.S. Geological Survey Professional Paper 1421–B, 61 p., 8 pl.

Fitterman, D.V., and Labson, V.F., 2005, Electromagnetic induction methods for environmental problems, *in* Butler, D.K., ed., Near-surface geophysics—Part 1, Concepts and fundamentals: Tulsa, Society of Exploration Geophysics, p. 295–349.

Flores, Robert, 1990, Test well drilling investigation to delineate the downdip limits of usable-quality groundwater in the Edwards aquifer in the Austin region, Texas: Texas Water Development Board Report 325, 70 p.

Geonics Limited, 2006a, Protem 47D operating manual for 20/30 gate model: Ontario, Geonics Limited, 80 p.

Geonics Limited, 2006b, Protem 57–MK2 D (C) operating manual for 20/30 gate model: Ontario, Geonics Limited, 58 p.

Geosoft, Inc., 2006, Oasis montaj—Software for earth science mapping and processing, version 6.3.1: Geosoft, Inc.

Grant, F.S., and West, G.F., 1965, Interpretation theory in applied geophysics—Part 3, Electrical conduction and electromagnetic induction methods: New York, McGraw-Hill, p. 384–572.

Halliday, David, and Resnick, Robert, 1974, Fundamentals of physics: New York, Wiley, 827 p.

Interpex Limited, 1996, TEMIX XL user's manual, version 4: Golden, Colo., Interpex Limited.

Lucius, J.E., Langer, W.H., and Ellefsen, K.J., 2007, An introduction to using surface geophysics to characterize sand and gravel deposits: U.S. Geological Survey Circular 1310, 33 p.

Keys, W.S., 1990, Borehole geophysics applied to ground water investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 2, chap. E2, 150 p.

Maclay, R.W., 1995, Geology and hydrology of the Edwards aquifer in the San Antonio area, Texas: U.S. Geological Survey Water-Resources Investigations Report 95–4186, 64 p., 12 pl.

National Geodetic Survey, 2006, Online positioning user service: accessed October 2006, at *http://www.ngs.noaa.gov/OPUS/*.

North Carolina Division of Water Resources, 2006, Time domain electromagnetic geophysics: accessed July 31, 2006, at *http://www.ncwater.org/Education_and_Technical_Assistance/Ground_Water/TDEM/*.

Senger, R.K., and Kreitler, C.W., 1984, Hydrogeology of the Edwards aquifer, Austin area, central Texas: Austin, Tex., University of Texas, Bureau of Economic Geology Report of Investigations 141, 35 p.

Slade, R.M., Jr., Dorsey, M.E., and Stewart, S.L., 1986, Hydrology and water quality of the Edwards aquifer associated with Barton Springs in the Austin area, Texas: U.S. Geological Survey Water-Resources Investigations Report 86–4036, 117 p.

Slagle, D.L., Ardis, A.F., and Slade, R.M., Jr., 1986, Recharge zone of the Edwards aquifer hydrologically associated with Barton Springs in the Austin area, Texas: U.S. Geological Survey Water-Resources Investigations Report 86–4062, 1 sheet.

Small, T.A., Hanson, J.A., and Hauwert, N.M., 1996, Geologic framework and hydrogeologic characteristics of the Edwards aquifer outcrop (Barton Springs segment), northeastern Hays and southwestern Travis Counties, Texas: U.S. Geological Survey Water-Resources Investigations Report 96–4306, 15 p.,1 pl.

Smith, B.D., Smith, D.V., Hill, P.L., Labson, V.F., 2003, Helicopter electromagnetic and magnetic survey data and maps, Seco Creek area, Medina and Uvalde Counties, Texas: U.S. Geological Survey Open-File Report 03–226, 11 p.

Stewart, M., and Gay, M.C., 1986, Evaluation of transient electromagnetic sounds for deep detection of conductive fluids: Ground Water, v. 24, p. 351–356.

Texas Water Development Board, 2006, Groundwater database downloads: accessed 2006, at *http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWDatabaseReports/GWdatabaserpt.htm*

U.S. Army Corps of Engineers, 1995, Geophysical exploration for engineering and environmental investigations: Engineering Manual 1110–1–1802, chap. 4, 57 p.

U.S. Geological Survey, 2006, National Water Information System (NWISWeb) data available on the World Wide Web: accessed 2006, at *http://waterdata.usgs.gov/tx/nwis/nwis*

Prepared by the USGS Lafayette Publishing Service Center.

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