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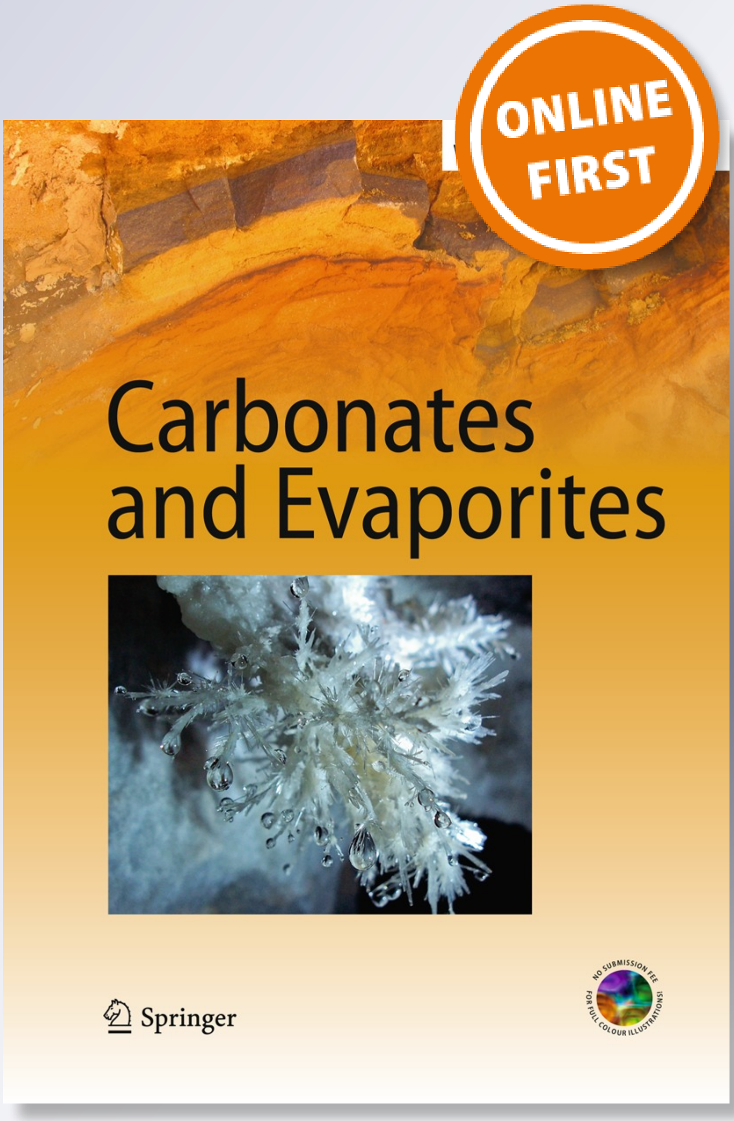

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ORIGINAL ARTICLE

Geophysical signatures of Barton Springs (Parthenia, Zenobia and Eliza) of the Edwards Aquifer, Austin, Texas

Mustafa Saribudak · Nico M. Hauwert · Alf Hawkins

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Abstract Barton Springs is a major discharge site for the Barton Springs Segment of the Edwards Aquifer and is located in Zilker Park in Austin, Texas. Barton Springs actually consists of four springs: (1) The Main Barton Springs discharges into the Barton Springs pool from the Barton Springs Fault and several outlets along a fault and from a cave, several fissures, and gravel-filled solution cavities on the floor of the pool west of the fault. The thin-bedded unit on the southwest side of the fault is the regional dense member, and the lower Georgetown Formation of the Edwards Group is exposed on the northeast side of the fault. The offset of the fault is between 40 and 70 ft (12–21 m). (2) Old Mill Springs is located in the sunken gardens southeast of the Barton Springs Pool and is primarily fed by relatively mineralized groundwater from the Saline-Line Flow Route. (3) Eliza Springs is also located along the Barton Springs Fault north of Barton Springs pool. (4) The Upper Barton Springs is located upstream of the Barton Springs pool on the south bank. Surface geophysical surveys [resistivity imaging and natural potential (NP)] were performed over the first three springs (Main Barton, Old Mill and Eliza Springs). Conductivity (EM) surveys were conducted in some areas to distinguish utility lines. The purpose of the surveys was to: (1) locate the precise location of submerged conduits carrying flow to Main Barton Springs on the north and south banks of the Barton Springs pool; (2) characterize the hydraulic relation between the Main Barton, Old Mill and Eliza Springs; (3) determine the potential location of caves and active flow paths beneath the three springs; and (4) characterize the geophysical signatures of the fault crossing the Barton Springs pool. The geophysical surveys revealed three general types of anomalies. Resistivity results from the south of the Barton Springs swimming pool indicate presence of a thick, laterally extensive high conductivity layer above the pool elevation. This high conductivity layer is interpreted to be lateral clay deposits, either associated with the Del Rio clay or clay-rich alluvial deposits associated with Barton Creek. These clay layers appear to overlie the Edwards Aquifer south of the pool. Also south and east of the pool are cylindrical high conductivity anomalies that extend deeper than the elevation of the submerged cave observed in Barton Springs pool. These cylindrical high conductivity anomalies are also associated with NP anomalies, suggesting groundwater flow. One hypothesis is that the alignment of the high conductivity and NP anomalies corresponds to the Saline-Line Flow Route that is known to discharge primarily at Old Mill Springs, and is hydraulically connected to Main Barton Springs and Eliza Springs. This hypothesis is favored because the Saline-Line Flow Route carries relatively mineralized groundwater and is known to connect to Old Mill Springs and at some times Main Barton and Eliza Springs. There are likely several conduit paths to the pool from the southern part of Zilker Park. Flow paths to Barton Springs from the east may be localized within the uppermost leached and collapsed members of the Edwards Group, which is known for its extensive horizontal cave development. A third type of

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anomaly, generally found west and immediately adjacent to the Barton Springs Fault, southwest of Barton Springs pool are circular low conductive features associated with NP anomalies. These circular anomalies are interpreted to be groundwater flow conduits bearing less mineralized groundwater associated with the Sunset Valley and possibly Manchaca Flow Routes that are expected to cross that area. The surveys allow an opportunity to compare geophysical responses to directly observed features. The Barton Springs Fault appears to be associated with circular high- and low-resistivity anomalies. Eliza and Old Mill Springs also indicate significant resistivity and NP anomalies suggesting presence of submerged conduits and faults in the vicinity. Although it is obvious such conduits are present adjacent to major springs, the surveys allow examination of how such water-filled conduits appear using various geophysical methods. Known underground infrastructure was also included in the surveys to see how air and water-filled pipes responded. An air-filled train tunnel corresponded to a high-resistivity anomaly. Local utility lines crossing the site showed no significant resistivity anomaly but metal pipes were detectable with EM conductivity surveys.

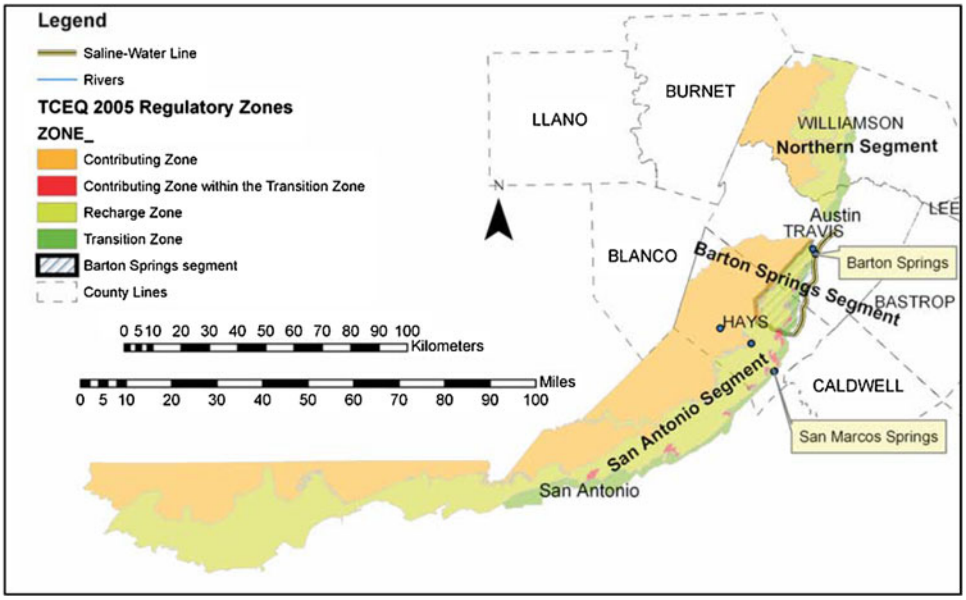
Introduction

Barton Springs discharge from the karstic limestone of Edwards Aquifer (Fig. 1). The structural framework of the Edwards Aquifer is controlled by Balcones Fault Zone (BFZ) an echelon array of normal faults that has extended and dropped the aquifer and associated strata from northwest to the southeast (Small et al. 1996; Ferril et al. 2005).

Barton Springs is a major discharge site for the Barton Springs Segment of the Edwards Aquifer into Barton Creek about 3,400 ft (1,000 m) upstream of its mouth at the Colorado River (Hauwert 2009, and see Fig. 2). The geologic framework is highly faulted near Barton Springs (Fig. 2). Fissures, conduits, and caves are commonly encountered throughout the Barton Springs. Barton Springs actually consists of at least four spring clusters, three of which were originally named after the daughters of the original owner of the Park, William Barton. The water feeding the springs is derived from mixtures of different sources, identified by distinct differences in water quality and injected tracer breakthroughs (Hauwert et al. 2004; Hauwert 2009).

1. The Main Barton Springs, or Parthenia Spring, discharges into the Barton Springs pool near the diving board at an obvious fault line. The thin-bedded unit on the southwest side of the fault is the regional dense member of the Edwards Group and is juxtaposed with the lower Georgetown Formation of the Washita Group which is exposed on the northeast side of the fault. The offset of the fault is estimated to be between 40 and 70 ft (12 and 21 m). Main Barton Springs is supplied by a mixture of flows from the Sunset Valley Flow Route, the Manchaca Flow Route, and the Saline-Line Flow Route (Hauwert et al. 2004).
2. Zenobia Spring is located in the sunken pool southeast of Main Barton Springs and is also called Old Mill Springs. This spring is primarily supplied by the Saline-Line Flow Route, which is enriched in highly mineralized water (Hauwert et al. 2004; Hauwert 2009). Hydraulic connection between Old Mill Springs

Fig. 1 Balcones Fault Zone portion of the Edwards Aquifer. Barton Springs are located in the Barton Springs Segment (from Hauwert 2009)



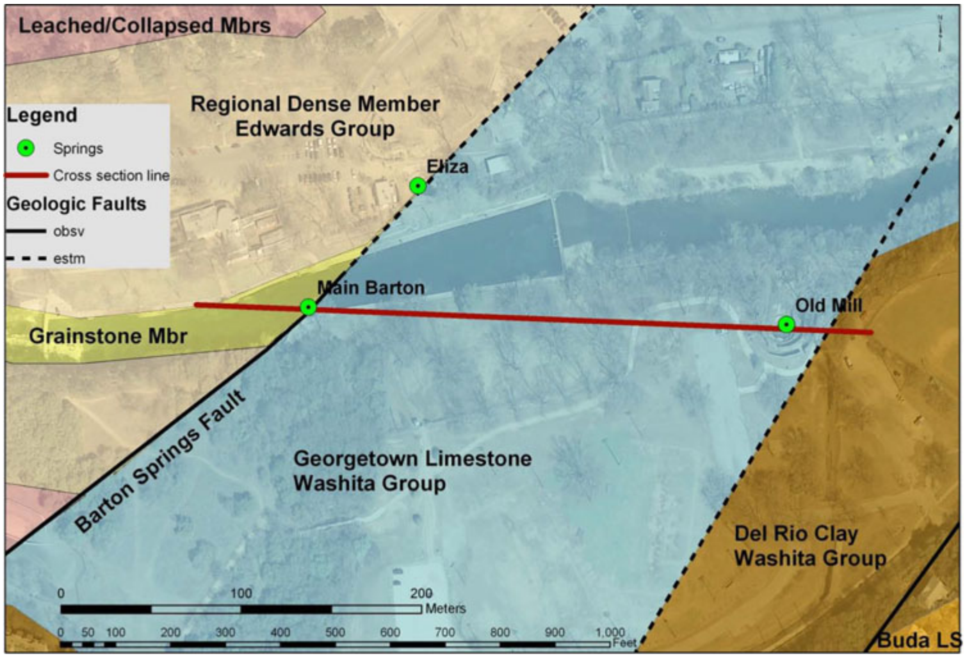


Fig. 2 Surface geology of the Barton Springs area (modified from Hauwert 2009). Note on this map that the Edwards Group members are exposed west of the Barton Springs Fault, while clays and limestones of the overlying Washita Group are exposed east of the fault

and Main Barton Springs is evident when Barton Springs pool draining results in the flow of Old Mill Springs to cease (Hauwert 2009).

3. Eliza Springs is located behind the concession stand and is also called Concession spring. Eliza Springs is primarily supplied by the Manchaca Flow Route of the Manchaca groundwater basin (Hauwert 2009)
4. The Upper Barton Springs is located upstream of the Barton Springs pool on the south bank. This spring is supplied solely from the Sunset Valley Flow Route (Hauwert 2009)

Based on local surface observations, a geologic cross section illustrates the site geology roughly along the south side of Barton Springs pool, from Main Barton Springs through Old Mill Springs (Fig. 3). This line was selected because it includes outcrops where the site geology is directly determined, although some geologic features, such as bedrock depth, the elevation of the contact between the Georgetown Formation and the underlying Edwards Group, and the location of an estimated fault near Old Mill Springs are not directly observed and are estimated based on available data.

In this study, geophysical survey methods (resistivity and natural potential) are integrated for the shallow subsurface characterization of Barton Springs (Main Barton, Old Mill and Eliza), their associated karstic features, and flow paths of the springs. These methods were chosen for their ability to rapidly map variations of their respective physical attributes (e.g., electrical resistivity and ambient electrical current).

Methods

Resistivity imaging (AGI SuperSting R1/swift system)

Resistivity imaging is a survey technique, which builds up a picture of the electrical properties of the subsurface by passing an electrical current along electrodes and measuring the associated voltages. Resistivity is the electrical resistance of a material and is inversely related to its electrical conductivity. This technique has been used widely in determining karst features and subsurface structures, such as faults and fractures. Used in this study was AGI's SuperSting R1 resistivity meter with a dipole–dipole electrode array that is relatively sensitive to horizontal changes in the subsurface than other arrays and provides a 2-D electrical image of the near-surface geology. Electrode spacing varied between 7 and 15 ft (2.1–4.6 m). High-resistivity (or low conductivity) anomalies may reflect air-filled voids, while low-resistivity anomalies may register clay-filled or high conductivity water-filled cavities.

Natural potential (NP)

Natural electrical (NP) currents occur everywhere in the subsurface. Karst investigations 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. Differences of potential are most commonly in the millivolts range and can be detected using a pair of non-polarizing

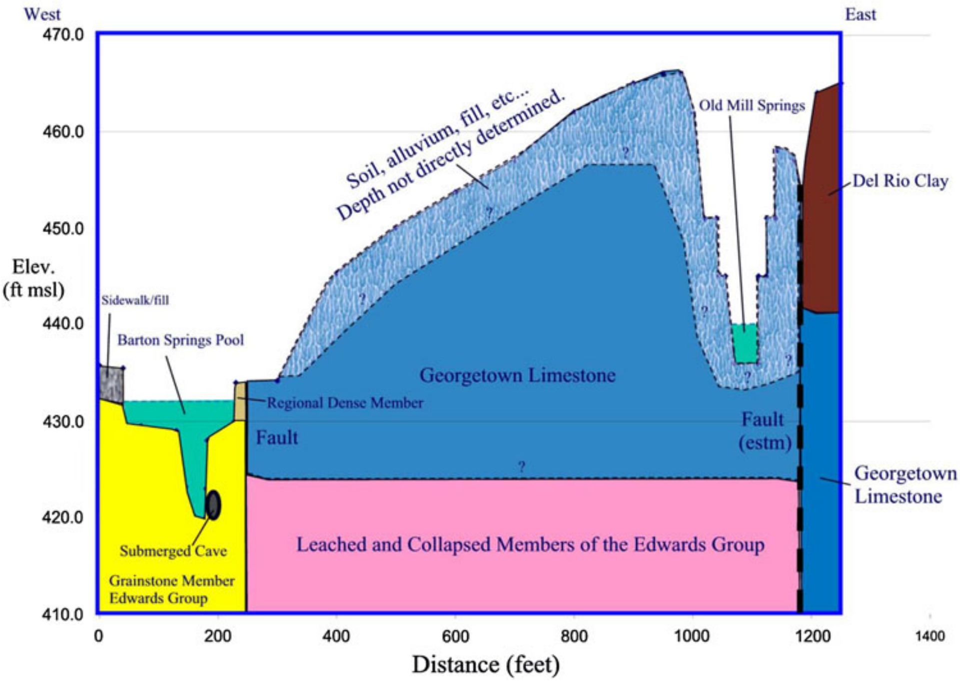


Fig. 3 Geologic cross section, based on field mapping, across Barton Springs Pool and Old Mill Springs

electrodes and a sensitive measuring device (i.e. a voltmeter). Recent flow of groundwater through a conduit is necessary for it to be detected using NP. Positive and negative NP values are attributed to changes in geometry of caves as well as variations in flow conditions. The source of NP anomalies can also be due to changes in topography or changing soil 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. For this reason, NP data are displayed together with the resistivity data. The NP data were also collected at a station spacing of 7 and 15 ft (2.1–4.6 m).

Because NP is a passive method (i.e., no energy was introduced during the testing), it was allowed within 100 ft (30 m) of endangered Barton Springs salamander habitat without the need to further demonstrate its safety or obtain a permit from the U.S. Fish and Wildlife Service.

Conductivity meter (EM31)

Conductivity surveys were performed using a Geonics model EM-31 instrument only in specific areas of Zilker Park south of Barton Springs pool gate. The EM31-MK2 conductivity unit maps the conductivity of the subsurface, and can detect metallic and non-metallic materials, geologic variations, buried materials, groundwater contaminants, or any subsurface feature associated with variations in ground conductivity. The EM-31 unit is a one-man unit with an intercoil spacing of 12 ft (3.7 m), which has an effective exploration depth of 18 ft (5 m), depending on the conductivity of the soil. The EM-31 conductivity is measured in units of milliSiemen/meter (mS/m). EM31 surveys were performed specifically to locate known and unknown utility lines in order to distinguish these from natural features.

Results

A total of 13 geophysical survey profiles were performed in and around the Barton Springs area (Fig. 4). Results are presented in Fig. 5 through Fig. 16. All geophysical profiles are presented from west (left) to east (right) or north (left) to south (right).

Line 1 Barton Springs Fault

Geophysical profiles along line 1 were directed to cross the Barton Springs Fault southwest of Barton Springs pool (Fig. 4). Although the Barton Springs Fault is not well exposed at this location, it is exposed in the pool only about 300 ft (90 m) northeast and extrapolated through local mapping (Small et al. 1996, Hauwert 2009). The resistivity data reflect the crossing of the Barton Springs Fault at station 95, read as feet along the survey line, where resistivity contrast is highest and signatures are vertically offset (Fig. 5). The resistivity profile also shows potential caves between stations 60 and 120 ft at depths between 10 and 35 ft (3–10 m), indicated by both high- and low-resistivity anomalies corresponding with a high NP anomaly. The NP anomaly peaks west of the fault (between stations 60 and

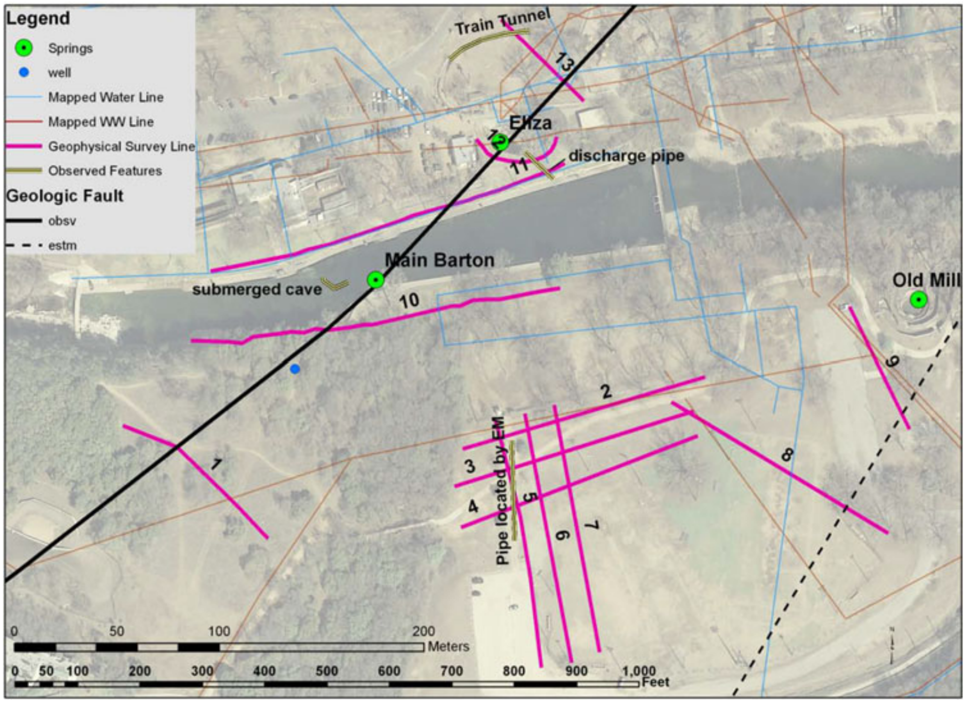


Fig. 4 Site map showing locations of Barton Springs, geophysical survey lines, mapped faults mapped utility lines and some observed features

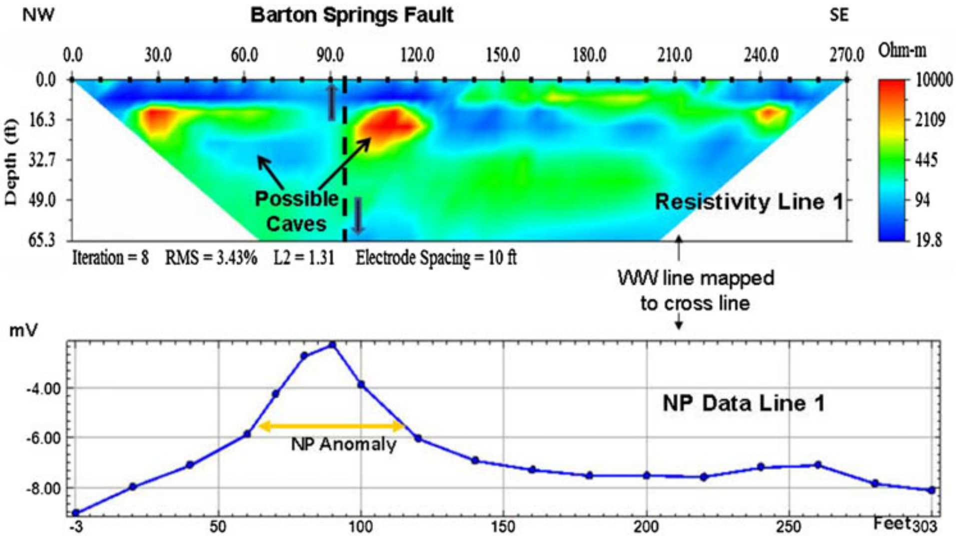


Fig. 5 Resistivity and NP data along line 1 crossing Barton Springs Fault southwest of the pool

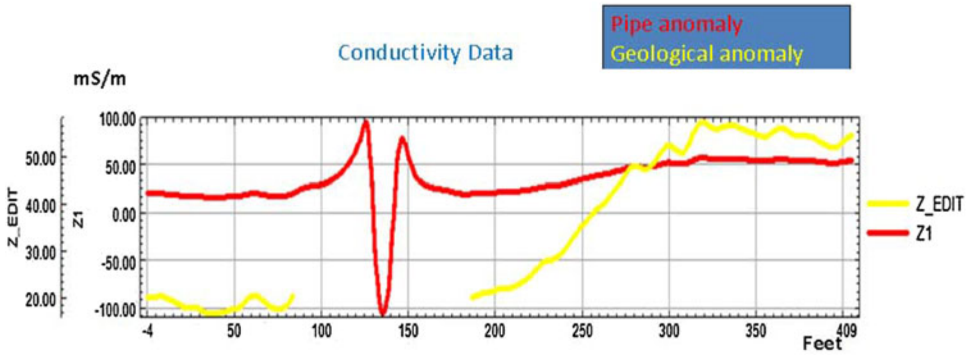
120 ft) where localized groundwater flow is interpreted. Within Barton Springs pool itself, flow can be observed discharging along the Barton Springs Fault, although most flow actually discharges from a horizontal cave developed in a ledge near the bottom of the pool about 40 ft (12 m) west of the fault. At times large flows can be observed issuing about 80 ft (24 m) west of the fault along the continuation of the same ledge. The observations of spring discharge within Barton Springs pool, the NP, and resistivity data consistently indicate the main groundwater flow conduits are located west of the fault near the south side of Barton Springs pool.

Note that the survey line crosses a known waste-water line, that is observed as a 10-in. (0.2 m) metallic pipe crossing the tributary to the North that does not reflect in either resistivity or NP results (Fig. 5).

Lines 2 through 7 South Zilker Park

A reconnaissance conductivity survey was taken in this part of the study area (Fig. 6). Conductivity results indicate a metallic pipe located at about 135 ft (41 m, see Fig. 4 for pipe location). The pipe was not mapped here on City of Austin utility line coverage. An example of the

Fig. 6 Conductivity data were collected along lines 2, 3 and 4. All lines showed a pipe anomaly as shown in this figure (see text for more discussion)



conductivity data showing the pipe is given in Fig. 5. The conductivity data were further processed by removing the pipe interference (Z_edit in Fig. 5). The residual data indicate a significant conductivity contrasts along the profile between stations 200 and 225 ft. This observation suggests a vertical contact (fault) between a low resistivity/high conductivity material (interpreted as clay) to the east and a higher resistivity/low conductivity material to the west (interpreted as limestone). One interpretation based on the geophysical survey and consistent with available local surface geology is that the estimated location of the fault shown extending through Old Mill Springs is actually about 500 ft (150 m) west from where it is interpreted in Fig. 2. This fault separates surface exposures of the Del Rio Clay to the east from the Georgetown Limestone to the west. A second interpretation is that clay-rich alluvium thickens to 15–20 ft (5–7 m) east of station 200 ft along the survey line 2. Geotechnical borings are necessary to determine the source of the clay material.

Six profiles, lines 2 through 7, were surveyed in front of the south gate of Barton Springs pool (Fig. 4). Three of the profiles (L2, L3 and L4) were taken in the East–West direction, whereas three other profiles (L5, L6 and L7) were surveyed in the North–South direction.

Line 2 was surveyed roughly west to east sub-parallel to the pool fenceline and crossing within 50 ft (15 m) of the south entrance gate to Barton Springs pool at station 110 ft (Fig. 7). A dirt road leading to the south gate of Barton Springs pool is marked on the resistivity data. The resistivity data show a significant very low-resistivity anomaly (dark blue in color) between stations 75 and 175 ft along the survey line, and extending to depths of about 80 ft (24 m). This feature is a thick conductive circular feature that has a sharp contact with a more resistive unit (green and red in color) at station 180 ft along the survey line.

The NP data along the same line show a NP anomaly between stations 50 and 165 ft (Fig. 7). This anomaly correlates well with the location of the circular conductive feature on the resistivity profile. The source of NP anomaly could be a submerged cave.

Figure 8 shows resistivity lines (3 and 4) and the NP data taken along the resistivity line 4. As in Fig. 7, both resistivity profiles indicate very low resistivity features such as a circular conductive feature in the western section of the profiles. These conductive anomalies make sharp contacts with the moderate resistivity layers (green in color) of 50–200 Ohm-m between stations 135 and 180 ft. It is possible that some of the low-resistivity anomalies near the dirt road in lines 2, 3,

Fig. 7 Resistivity and NP data along line 2 that parallels the south gate fence. Note the sharp, shallow resistivity contrast at 135 ft. There is a significant NP anomaly indicating a water-filled cave or conduit where the low resistive anomaly is located

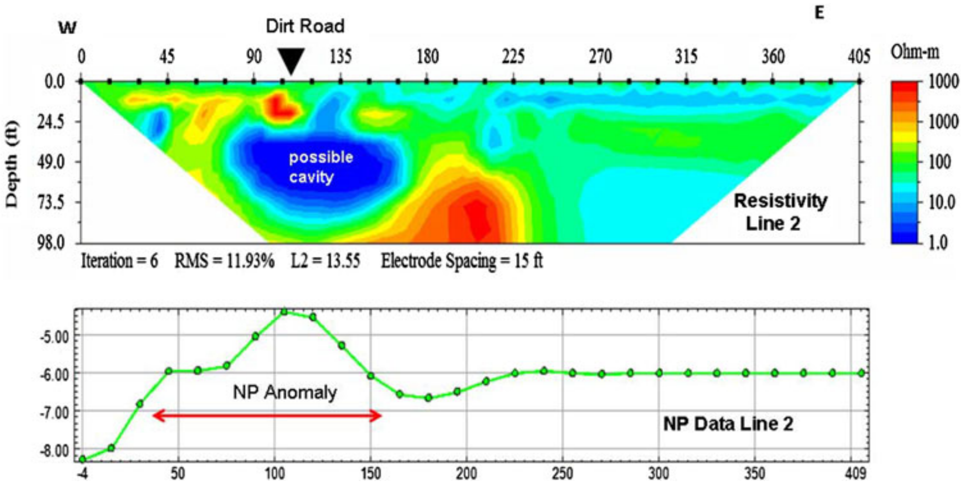
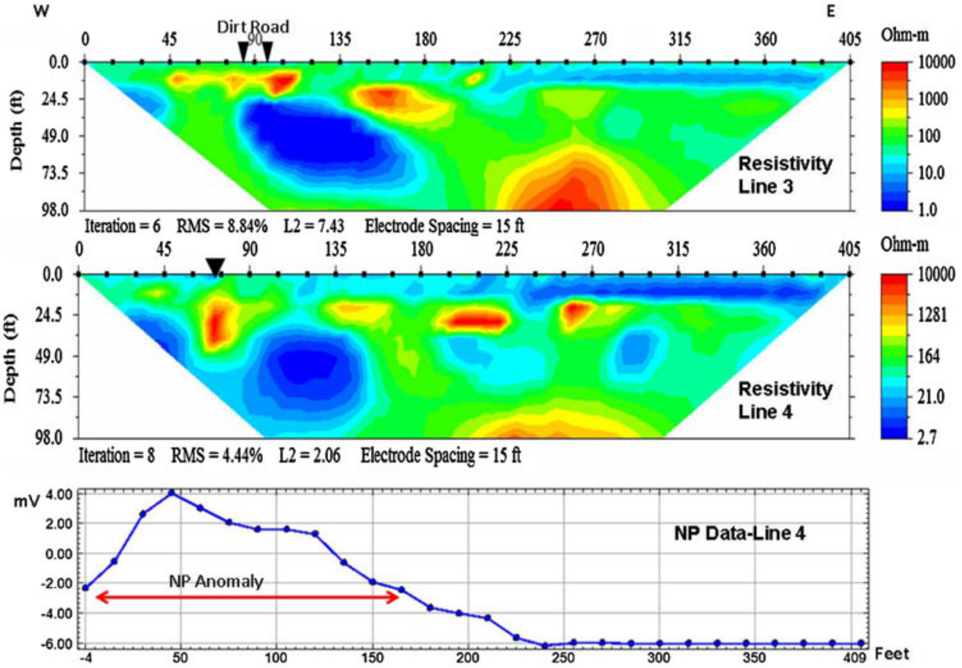


Fig. 8 Resistivity and NP data along lines 3 and 4 that run roughly west to east across a field near the south gate. Note the *blue* conductive and associated NP anomalies below the pool level and bedrock that could represent water-bearing solution features



and 4 may be affected from the metal pipe identified using EM conductivity, although generally the spacing is expected to be too big to be influenced by small-scale pipes.

The NP data, which were taken along line 4, show an NP anomaly between stations 0 and 150 ft. This anomaly correlates well with the location of a bedrock conductive unit on the resistivity profile. The source of NP anomaly could be a cave that is located beneath or around a clay-rich unit.

Figure 9 shows the North–South resistivity data along lines 5 and 6, and the NP data taken along line 6. Lines 5 and 6 are separated about 50 ft (15 m). The NP data were collected on a dry day and later repeated on a wet day to observe the effects of varying flow conditions. Both resistivity data sets indicate shallow (<20 ft or 7 m deep) horizontally extensive conductive features that could represent clay-rich layers. This low resistivity/conductive feature has a characteristic sharp geometry with the surrounding rock units. In addition, line 6 shows two well-defined circular conductive features at a greater depth below about 30 ft. A moderate resistive rock material (i.e., 100 Ohm-m) is observed between the two circular conductive features. Also a sharp offset in resistivity features, possibly fault, is observed at station 200 ft. The deeper circular conductive features could represent caves bearing relatively mineralized solution, or conductive mineral/clay coating on the conduit wall (i.e. fracture skins).

The NP data, which were taken along line 6, show a pair of NP anomalies between stations 0 and 100 ft, and stations 150 and 200 ft, respectively. The source of both NP anomalies could be a water-bearing cave.

Figure 10 shows the same resistivity data from lines of 5 and 6 with the NP data that were collected the next day after a big rain, which caused the Barton Springs pool to close for several days due to the flooding of Barton Creek. The pair of NP anomalies observed in Fig. 9 during a dry day was integrated into one large NP anomaly between stations 50 and 200 ft during wet conditions. This observation indicates that the groundwater in the cave or conduit, which was charged by the recent rain, elevated the groundwater level and enlarged the NP anomaly.

Figure 11 shows the resistivity and NP data of line 7 (see Fig. 3 for location). Line 7 is located 50 ft (15 m) east of line 6. The resistivity and NP data sets do not indicate any significant anomaly. The NP data of line 7 could reflect simply a hydraulic gradient of groundwater decreasing toward the Barton Springs pool. Line 7 seems to reflect a background section where no significant resistivity or NP anomalies are present.

Lines 8 and 9 Old Mill Springs

Lines 8 and 9 were collected to the southwest and south of Old Mill Springs, respectively (Fig. 4). Figure 12 indicates the resistivity and NP data taken along line 8. The resistivity data indicate a pair of low and high anomaly located between stations 60 and 105 ft. There is a known wastewater line crossing this profile. It is not clear if the wastewater pipe is the source for this resistivity anomaly. The NP data indicate an anomaly between stations 290 and 390 ft. The relatively mineralized Saline-Line Flow Route

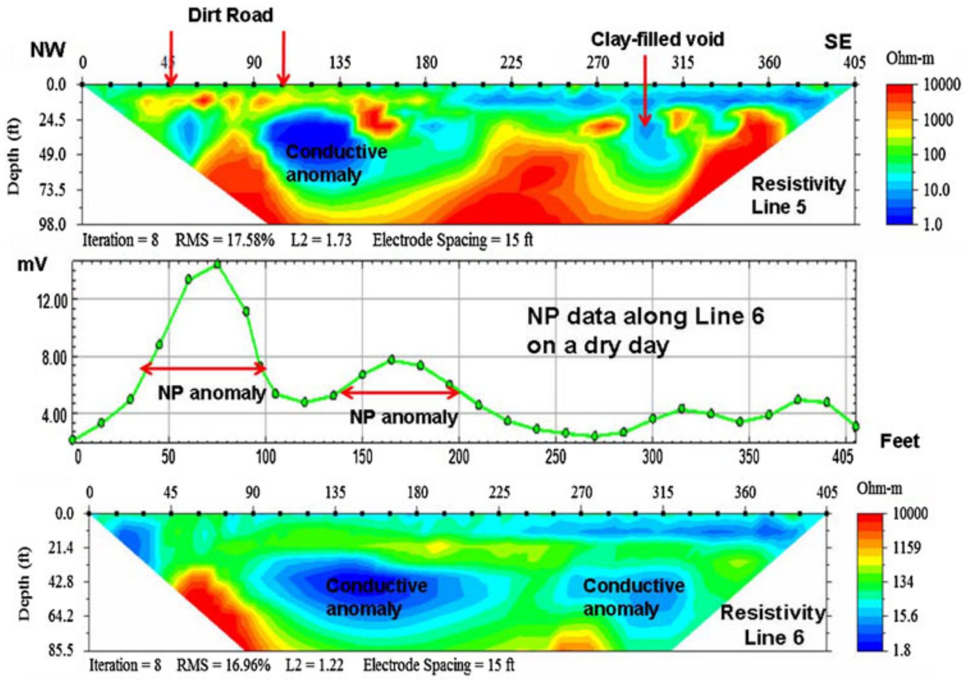


Fig. 9 Resistivity and NP data along lines 5 and 6. The NP data were collected on a dry day

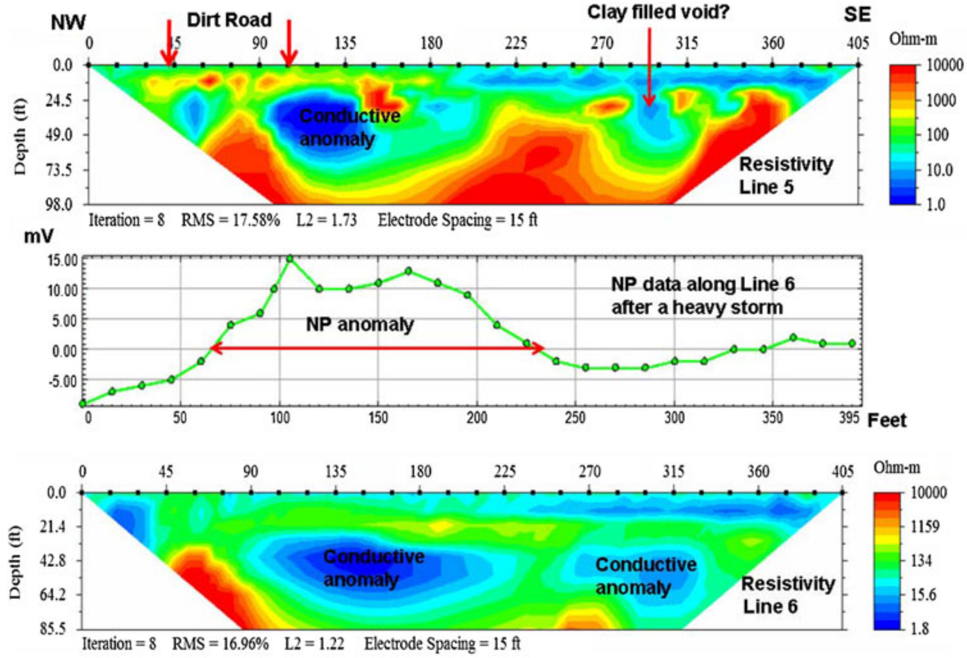


Fig. 10 Resistivity and NP data along lines 5 and 6. The NP data were collected 1 day after a heavy storm

is known to pass through this area toward Old Mill Springs (Hauwert 2009).

Line 9 was surveyed to the west of Old Mill Springs, and is shown in Fig. 13 (see Fig. 4 for location). The resistivity data show a pair of low- and high-resistivity anomalies located between stations 60 and 120 ft. The contrast between the two is quite sharp, and the maximum depth of this anomaly is observed down to 50 ft (15 m). The groundwater discharges from Old Mill Springs at an elevation about 20 ft (6 m) below the line 9 surface closest to Old Mill Springs. The NP data also indicate a NP anomaly between stations 50 and 110 ft, corresponding to areas of resistivity anomaly.

Lines 10 and 11 Barton Springs pool

Only NP surveys were allowed to perform inside the fences of the Barton Springs pool due to potential for impacts

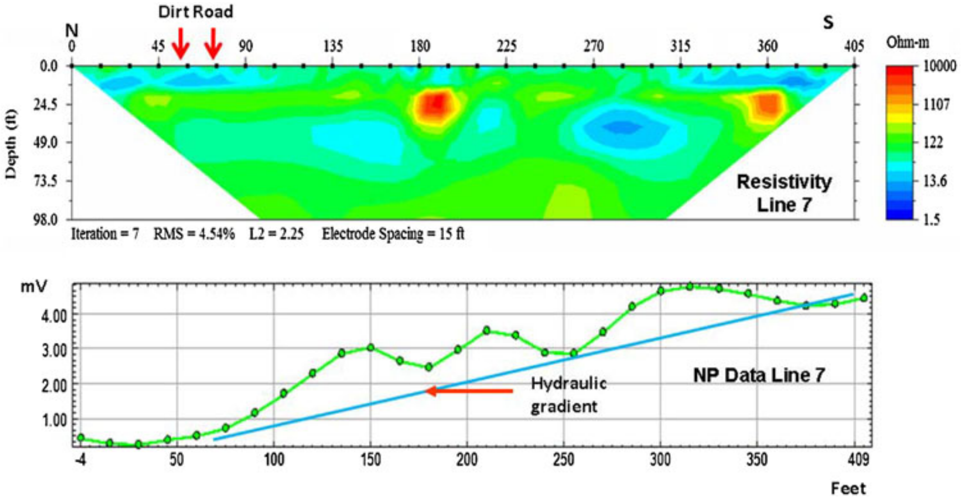


Fig. 11 Resistivity and NP data along line 7 that crosses north to south across a field South of Barton Springs pool. Both data sets do not indicate any significant anomaly. Note the hydraulic gradient on NP data, which is toward the north where the Barton Springs pool is located

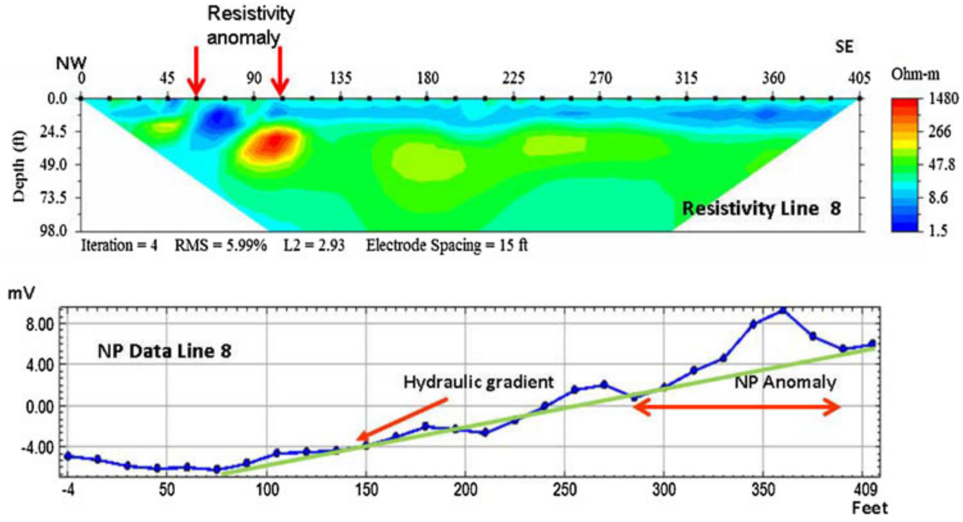


Fig. 12 Resistivity and NP data along line 8. The resistivity anomaly observed between 60 and 100 ft is not associated with NP anomalies. Note the sloping NP data are interpreted to reflect decreasing hydraulic gradient towards the Barton Springs pool

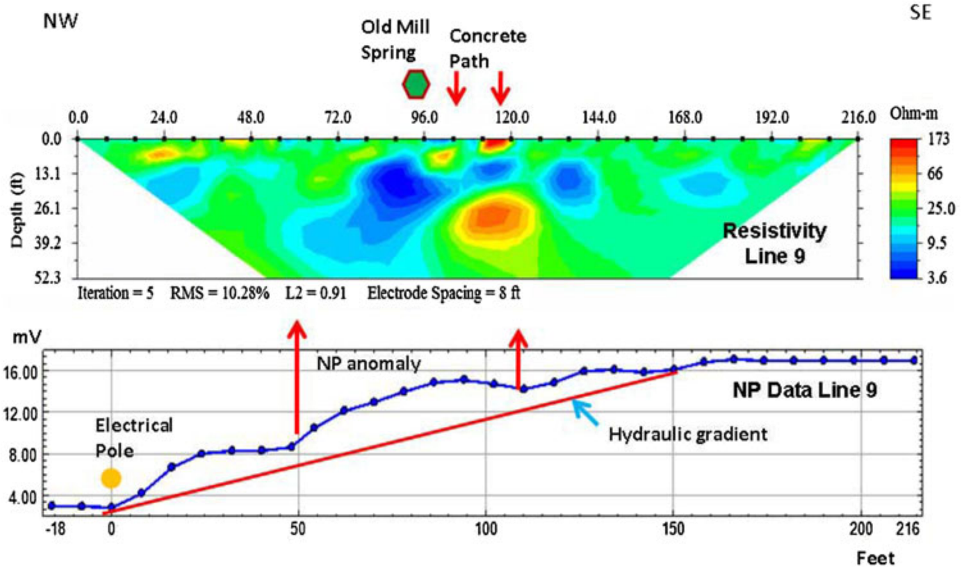


Fig. 13 Resistivity and NP data along line 9 next to Old Mill Spring. A pair of high- and low-resistivity anomalies corresponds to an NP anomaly

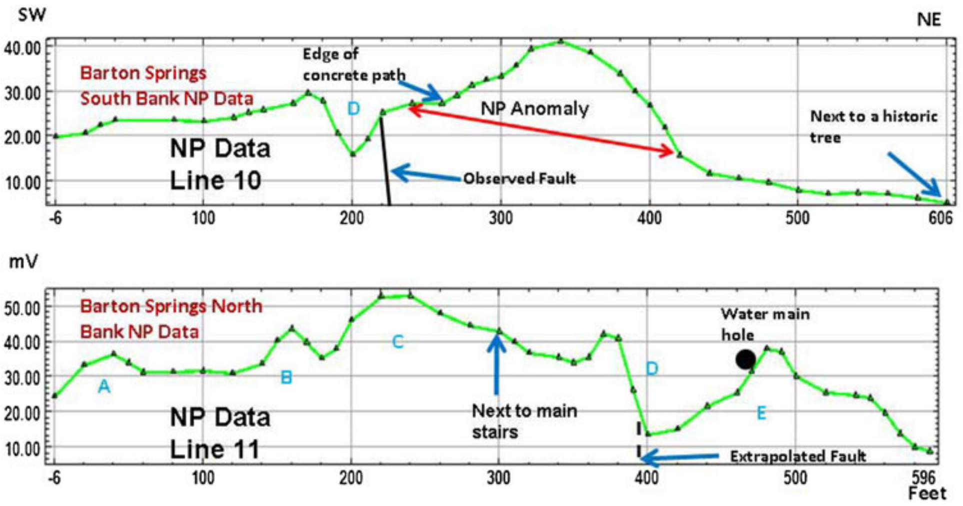


Fig. 14 NP data along the south and north banks of Barton Springs pool. The northern bank has more NP anomalies than the southern bank. The anomaly D on both profiles corresponds to the location of Barton Springs Fault

from resistivity surveys on endangered species of aquatic salamanders living in the pool. Thus two NP lines, 10 and 11, were surveyed along the southern and northern banks of the pool (see Fig. 4 for location). Figure 14 shows both NP data profiles. Locations of some cultural features along the profiles are shown as reference points. Note that an 8 ft (2.4 m) high, 10 ft (3 m) wide concrete bypass culvert structure underlies the sidewalk adjacent to the northern side of Barton Springs pool. This bypass structure carries flow from upstream Barton Creek, discharge from Eliza Springs, and some leakage from the pool and underlying groundwater flow.

The north bank NP profile indicates more NP anomalies than the southern one. It shows basically four anomalies, which are marked on the profile as A, B, C, D and E. Sources for these anomalies could be due to water-bearing karstic features such as caves, voids, fractures and faults, as well as anthropogenic discharge pipes. Line 11 on the north bank generally lies 10–20 ft (3–6 m) away from the bypass, and is not affected by water that continually flows though the bypass, except for the area near anomaly C, which approaches within 3 ft (1 m) of the bypass.

The NP data on the south bank indicate a very significant NP anomaly D between stations 240 and 420 ft. This anomaly corresponds to where the Barton Springs Fault crosses the pool (see Fig. 3). There is another NP anomaly C located between stations 160 and 220 ft. Anomaly C could potentially reflect flow through the bypass, although water can be observed rising from the floor of the bypass in several places near anomalies C and D, that likely indicates groundwater flow passing beneath.

Lines 12 and 13 Eliza Springs

Recent boring information from the area north of Eliza Springs has verified the location of the Barton Springs Fault is consistent with the mapped location shown in Fig. 2. Lines 12 and 13 were surveyed to the east and west of Eliza Springs, respectively (see Fig. 4 for location). The NP data for line 12 were collected along a curved line around Eliza Springs (Fig. 15). The NP data indicate a steep NP anomaly between stations 70 and 140 ft. This anomaly is probably due to discharge into and out of Eliza Springs pool, including a known 2-ft diameter concrete pipe that discharges to the bypass structure adjacent to the north side of Barton Springs pool.

Line 13 was surveyed 150 ft to the east of line 12 (see Fig. 4 for location). Figure 16 shows the resistivity and NP data taken along line 13. The resistivity data indicate a pair of low- and high-resistivity anomalies between stations 100 and 150 ft with a sharp contact boundary between them. The NP data for line 13 indicate a low-NP anomaly between stations 100 and 150 ft. This anomaly corresponds to where the pair of low- and high-resistivity anomalies is observed, and probably caused by a submerged cave. The NP data also show a fault-like anomaly and appears to be accentuated by the hydraulic gradient toward the pool. A high-resistivity anomaly and low-NP anomaly are observed at station 30 ft, which appears to correlate to a train tunnel for a small-gage recreational train that serves Zilker Park.

Discussion

Geophysical surveys of Barton Springs pool may provide details on locations of discrete groundwater flow that would otherwise require many potentially disruptive wells to decipher. While the geophysical results are subject to interpretation and require prior experience to identify, they reveal properties of the Barton Springs pool area that can be further investigated with focused follow-up studies. The significant anomalies are mapped on Fig. 17.

Fig. 15 NP data along line 12 next to Eliza Springs. Note that NP anomaly indicates where flow conduits carry flow to or from Eliza Springs. A known artificial subsurface discharge pipe is also reflected as an NP anomaly

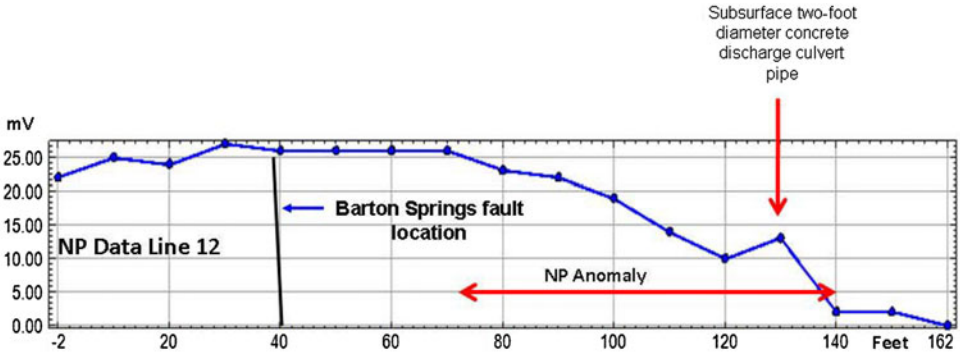


Fig. 16 Resistivity and NP data along line 13. WP1 and WB3 are borehole locations. WP1 was later converted into a monitoring well. Both borehole data sets indicate paleo-channel materials between the depths of 15 and 35 ft. Note how the train tunnel is reflected in the resistivity survey

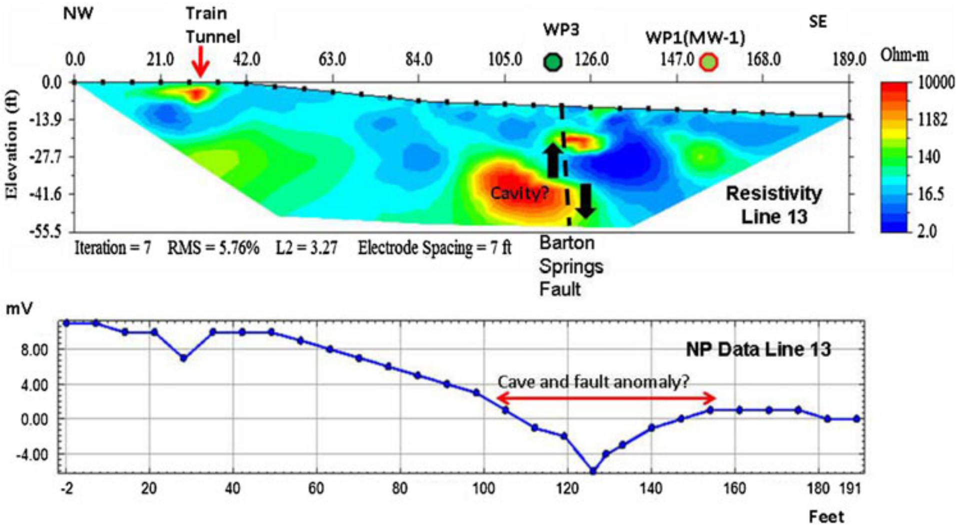
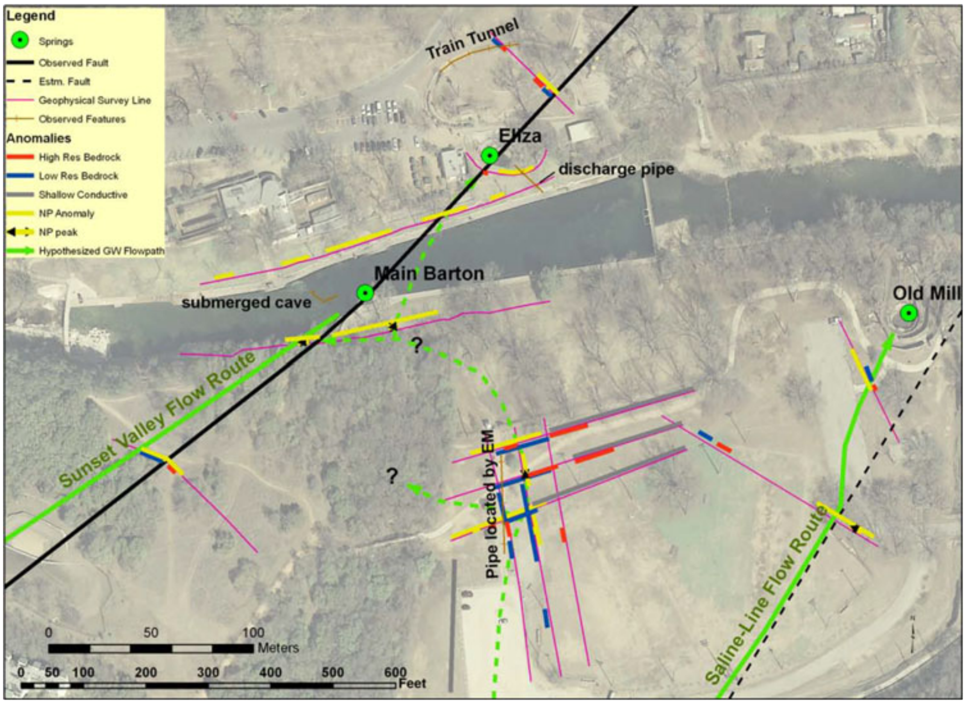


Fig. 17 Summary of geophysical anomalies detected around Barton Springs pool. One interpretation of a groundwater flow path to Main Barton and Eliza Springs is consistent with the survey results is shown, although other interpretations are possible, including that some of the south NP anomalies are associated with shallow perched groundwater flow through alluvial deposits



Deeper circular low resistivity/high conductivity features are localized in specific areas south of Barton Springs pool and extend vertically to depths of about 30 ft (9 m) to as deep as 80 ft (24 m). Since the circular conductive features were encountered in East–West lines of 2, 3, and 4; and North–South lines of 5 and 6, they are most likely cylindrical features. It corresponds with the depth of the submerged cave in Barton Springs pool whose elevation of 423 ft (129 m) msl is about 43 ft (13 m) deep below Line 2. It is unlikely that either anthropogenic fill, gravel quarrying, or alluvial fill would occur below the constantly flowing base level of adjacent Barton Creek and regional base level of the nearby Colorado River (410 ft or 125 m msl; Solis et al. 2009). The 410 ft msl elevation is also the deepest depth where terrace alluvial materials were encountered by borings along the north side of Barton Creek from Barton Springs pool to the Colorado River (Fugro 2003). As NP anomalies, these features appear to correspond with flowing groundwater. Therefore, the circular conductive features must be submerged bedrock features, likely water-filled caves or a clay-filled, flow conduit to Barton Springs.

One hypothesis is that the prominent low-resistivity anomalies southeast of the pool are flow conduits from the Saline-Line Flow Route to Main Barton and Old Mill Springs. Chemical analysis of flow discharging from Main Barton Springs suggests that mixing with the Saline-Line Flow Route has already occurred as it discharges from the south side of the pool at the Barton Springs Fault (Hauwert et al. 2004). Yet flow from the Manchaca Flow Route appears to arrive at Eliza that does not contain Sunset Valley Flow Route contributions. Therefore, the source of Eliza Springs must include a slightly deeper flow path passing beneath the pool that does not contain Sunset Valley Flow Route mixing. So a second hypothesis could be that the cylindrical resistivity anomalies and NP anomalies near the south gate are sensing the Manchaca Flow Route to Main Barton and Eliza Springs.

Without resistivity surveys (which were not permitted in the pool area for this study as a precaution for the endangered salamanders), it is unclear if NP anomalies on the southeast side and adjacent to the pool are associated with NP anomalies near the south gate. Also unclear without resistivity surveys is the depth of any groundwater-bearing conduits below the southeast side of the pool. The southeast pool NP anomalies could reflect a number of hydrogeological conditions including (1) groundwater following shallow paleodrainage channels in the alluvium, as seeping water is constantly observed crossing the side pool sidewalk here, (2) solution cavities and fissure planes filled by pool backwater, or (3) unobserved bedrock discharge orifices located in the deep eastern end of the pool. The southeast pool NP anomalies could reflect flow paths that cross underneath the pool and Georgetown Formation and discharge from Eliza Springs. The NP data obtained from the banks of Barton Springs Pool also indicate correlating conduit anomalies along the Barton Springs Fault.

NP and resistivity surveys reveal anomalies next to Old Mill Springs (Fig. 12 and 13). The resistivity data indicate a significant geological contact, which could be a fault, between a pair of low- and high-resistivity anomalies. The depth of these anomalies is about 35 ft (11 m) deep and lies lower than the water-level of Old Mill Springs which is roughly 20 ft (6 m) below line 9. This further supports the hypothesis that mineralized groundwater flow associated with the Saline-Line Flow Route is associated with low resistivity/high conductivity and an NP anomaly. NP anomalies encountered on lines 8 and 9 are consistent with the crossing of the Saline-Line Flow Route to Old Mill Springs.

There is a fault estimated to the east of Old Mill Springs based on outcrop mapping and geotechnical borings on the opposite side of Barton Creek (Fig. 17). The NP data show an anomaly, likely localized groundwater flow, where the fault is extrapolated; however, the resistivity data do not indicate offset structures or high resistivity contrast in this location. A fault contact between limestone and clay, if present, should be clearly discernable on a resistivity survey. It is possible that the actual fault location is further west or that the fault is reflected here as an eastward dipping monocline rather than an abrupt fault.

The resistivity data obtained across the Barton Springs Fault in the southern portion of Zilker Park (line 1 see Fig. 17 for location) show highest resistivity contrast where the Barton Springs Fault is mapped. An NP anomaly peaks just northwest of the extrapolated fault location, suggesting most flow is localized in the grainstone and underlying kirschberg members on the upthrown side of the fault. The elevation of a submerged cave in Barton Springs pool (423 ft or 129 m msl) is 40 ft (12 m) lower than line 1 at the extrapolated Barton Springs Fault crossing 463 ft or 141 m msl. A low-resistivity anomaly is shown slightly higher than this depth at the same station as the NP anomaly peak. This low-resistivity anomaly may be an extension of the cave observed in Barton Springs pool west of the Barton Springs Fault, which is about 375 ft (114 m) to the northeast.

NP data to the east of Eliza Springs indicate significant anomalies. In addition, the resistivity data indicate a pair of high- and low-resistivity anomalies that identify the Barton Springs Fault. The NP anomaly suggests groundwater flow, beyond the known pipe that discharges Eliza Springs flow into the bypass. One explanation could be groundwater flowing to Eliza Springs from the north. Another explanation that may be more likely is groundwater flow bypassing Eliza Springs along the Barton Springs Fault that discharges in the Colorado River.

Resistivity results obtained from the southern part of the Barton Springs pool indicate shallow low resistivity (high conductivity) laminar features similar in property to clay-rich units extending to depths of about 20 ft (6 m). Resistivity results obtained to the northeast of Eliza Springs also indicate a thick clay unit (~20 ft, 6 m, or more). This unit appears to sit on the Edwards Aquifer on the west side of the Barton Springs Fault. The shallow low resistivity signatures east of Eliza Springs on line 13 are similar to the ones that are observed in the southern side of the Barton Springs pool east of the south gate. Boring logs from geotechnical holes drilled here indicate that a dark reddish brown alluvial clay is present along the eastern end of line 13 to depths varying from 15 to 35 ft (Fugro 2003).

One of the most interesting findings is the geophysical responses at shallow observable features. In line 13, an air-filled train tunnel is associated with a high-resistivity anomaly and a low-NP anomaly. It is expected that an air-filled tunnel would be associated with a high-resistivity anomaly. Line 12 crossed a subsurface pipe carrying discharge from Eliza Springs and showed a distinct NP anomaly in that portion of the survey line. Future studies could focus geotechnical borings or monitor well drilling at the anomaly locations to verify the surface geology and existence of submerged caves. Furthermore, more detailed water-quality sampling and dye-tracing recovery from these local wells as well as various spring discharges in Barton Springs pool, the bypass, and Barton Creek may help distinguish the location of specific flow paths. Previous water-quality sampling (Hauwert et al. 2004) suggests that the major groundwater flow routes and their mixtures are generally distinguishable based on chloride and sulfate concentrations alone.

Conclusion

In summary, resistivity and NP results from the southern part of the study area indicate presence of a thick, widespread clay unit that appears to lie on the top of the Edwards Aquifer. Cylindrical low resistivity/high conductivity anomalies associated with NP anomalies below the bedrock south of the pool and east near Old Mill Springs are hypothesized to represent groundwater flow conduits associated with the relatively mineralized Saline-Line Flow Route. NP anomalies from the banks of Barton Springs pool may suggest where these Saline-Line flow conduits cross beneath the pool (Fig. 17). Circular high-resistivity/low-conductivity features associated with NP anomalies adjacent to and west of the Barton Springs Fault are hypothesized to reflect groundwater conduits for the Sunset Valley and possibly combined Manchaca Flow Routes that are know from previous studies to approach Barton Springs from this direction. Resistivity surveys near observed faults invariably show paired high and low contrasting resistivity signatures and may show offsets in layered structures. While some uncertainty remains for the exact groundwater flow paths near Barton Springs, the geophysical surveys do provide specific sites were groundwater flow can potentially be directly examined using borings or wells.

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