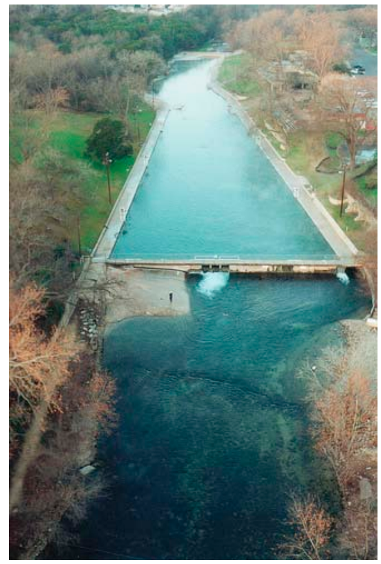
Fieldtrip Guidebook

Recharge Enhancement, Multiport Well Monitoring, Geophysics, and Springflow: Barton Springs Segment of the Edwards Aquifer, Central Texas



October 15, 2011

Prepared for:

Association of Environmental & Engineering Geologists
Texas Section

ENVIRONMENTAL ENGINEERING GEOLOGISTS AEG

Barton Springs Edwards Aquifer
CONSERVATION DISTRICT

"Committed to conserving, protecting, recharging, and preventing waste of groundwater and to preserving all the aquifers in the District"

City of Austin
WATERSHED PROTECTION

Recharge Enhancement, Multiport Well Monitoring, Geophysics, and Springflow: Barton Springs Segment of the Edwards Aquifer, Central Texas

Saturday October 15, 2011

Fieldtrip Speakers

Brian B. Hunt, P.G., and Brian A. Smith, Ph.D., P.G.
Barton Springs/Edwards Aquifer Conservation District

David Johns, P.G., and Nico Hauwert, Ph.D., P.G.
City of Austin Watershed Protection and Development Review

Mustafa Saribudak, Ph.D.
EGA, Houston Texas

Overview:

The karstic Barton Springs segment of the Edwards Aquifer is an important groundwater resource for Central Texas providing drinking water to more than 60,000 people and whose iconic springs are an important recreational feature for Austin, and habitat for endangered species. This fieldtrip will focus on some recent studies and projects the District and the City of Austin scientists have conducted to improve our understanding of the aquifer system and the quality of water recharging the aquifer. The field trip will visit Antioch Cave (**Stop 1b**), the largest discrete recharge feature in the aquifer, and a unique engineered structure built to enhance the quality and quantity of the water recharging the aquifer through Antioch Cave. The structure includes a concrete vault with an automated valve constructed over the entrance to Antioch Cave in the bed of Onion Creek. It is designed to prevent storm waters from going into the cave when sediment, bacteria, and other contaminants are high, and then allows cleaner water to flow into the cave when turbidity levels are lower. Nearby (**Stop 1a**), participants will see a demonstration of a multiport (Westbay) monitor well. The District has collected water chemistry and head data from 21 zones in the Edwards and Trinity aquifers and have gained considerable insight to the relationship between the two aquifer systems. After lunch, participants will visit Barton Springs (**Stop 2**), the 4th largest spring in Texas. Discussion at the springs will cover the challenges of managing the pool for endangered species and swimmers, protection of water quality in the Barton Springs Zone, karst hydrology and groundwater flow--especially dye tracing studies that have been conducted for more than a decade, and include case studies of difficulties with development in karst terrains. Additional discussions and presentations will include geophysical work identifying faults and groundwater conduits at both stops 1 and 2.

Contributors/Speakers:

Nico Hauwert, Ph.D., P.G. Nico completed a PhD and BS in Geology at UT and a MS in Geology from U. of Toledo. From 1993-2000 he conducted research on the Barton Springs Segment as Assessment Program manager and senior hydrogeologist for the Barton Springs/Edwards Aquifer Conservation District. Nico works as senior hydrogeologist and senior environmental scientist for the City of Austin Watershed Protection Dept. He served as Vice President for the Austin Geological Society from 1998-1999 and president from 2000-2001.

Brian Hunt, P.G., Brian graduated from UT Austin with B.S. and M.Sc.degrees in geological sciences. Brian is a Senior Hydrogeologist for the Barton Springs/Edwards Aquifer Conservation District and has worked for the District for more than 10 years.

David A. Johns, P.G. David has a B.S. degree in Geology from Texas A&M University and a M.A. degree in Geology from UT Austin. He worked at the Bureau of Economic Geology at UT before starting at the City of Austin. David has worked for the City of Austin for 22 years and is currently hydrogeologist in charge of geologic and hydrogeologic elements of water resources programs.

Mustafa Saribudak, Ph.D., P.G. Mustafa went to Istanbul University in Turkey for his geological engineering degree and he received his Ph.D. from the Geophysical Department of Istanbul Technical University. He worked on a National Science Foundation project at the Geosciences Department of Univ. of Houston and he worked for Tierra Environmental in the Woodlands, Texas. He founded Environmental Geophysics Associates in 1994 to provide near-surface geophysical services for engineering, environmental, oil and gas industries.

Brian A. Smith, Ph.D., P.G. Brian received his BA in Geology from Rice University and his Ph.D. in Geology from UT Austin. Brian is Aquifer Science Team Leader and has worked at the Barton Springs/Edwards Aquifer Conservation District for more than 10 years.

Acknowledgements:

This trip was organized following a suggestion by Jim Sansom, P.G.. We thank him for making all the contacts among the interested parties to bring this trip about. Robin H. Gary contributed some of the maps and figures in the guidebook. The District's Board of Directors and General Manager Kirk Holland, P.G. support this type of outreach and we thank them for their continued support of science and the dissemination of information. Kristen Scheller provided the logistical support of arranging for hotel and lunch accommodations.

Itinerary

8:00 am — Coffee and registration

8:30 am — Introductions

Jerry McCalip

8:45 am — Overview of fieldtrip and stops; presentations of topics visited

Brian A. Smith and Brian B. Hunt (BSEACD)
Mustafa Saribudak, Ph.D., EGA

9:45 am — Depart hotel; car pooling is recommended.

10:00 am — **STOP #1a: Westbay Multiport Monitor well.** View multiport monitor well demonstration.

Brian A. Smith and Brian B. Hunt

11:00 am — **STOP #1b: Antioch Recharge Enhancement Facility** on Onion Creek. Visit cave entrance and BMP that is used to enhance recharge to the Edwards Aquifer.

Brian A. Smith and Brian B. Hunt

11:45 pm — **STOP #1c: Geophysics.** Discussion of the results from a resistivity and natural potential (NP) geophysical work along Onion Creek and the faults.

Mustafa Saribudak, Ph.D., EGA

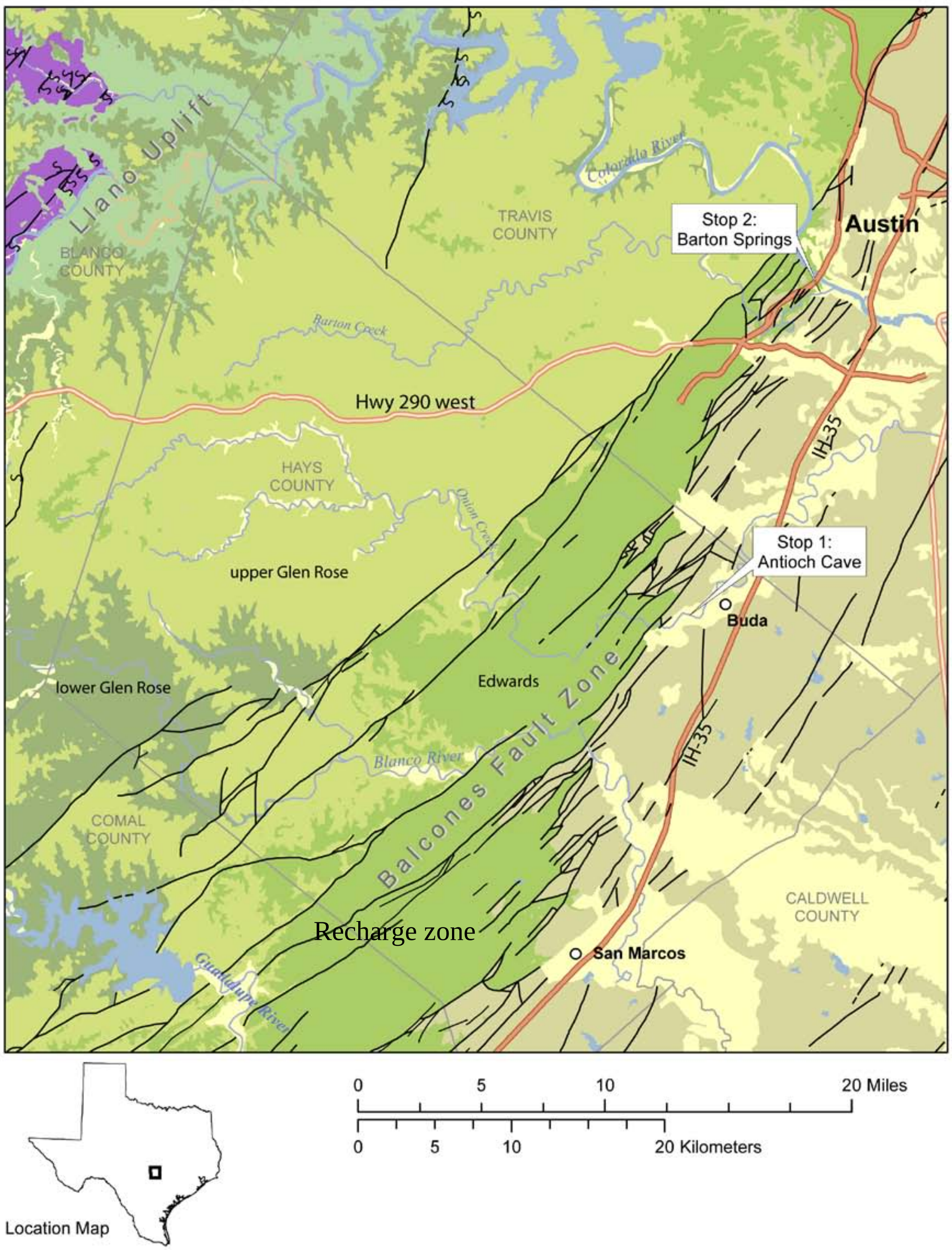
12:30 pm — Depart for box lunch and Stop 2 at Barton Springs (return to hotel and then head to Stop 2 Barton Springs)

1:45 pm — **STOP #2: Barton Springs**. Discussion about Barton Springs, dye tracing and other topics related to the springs.

David Johns, P.G., and Nico Hauwert, Ph.D., P.G., (City of Austin)

3:15 pm — End of fieldtrip

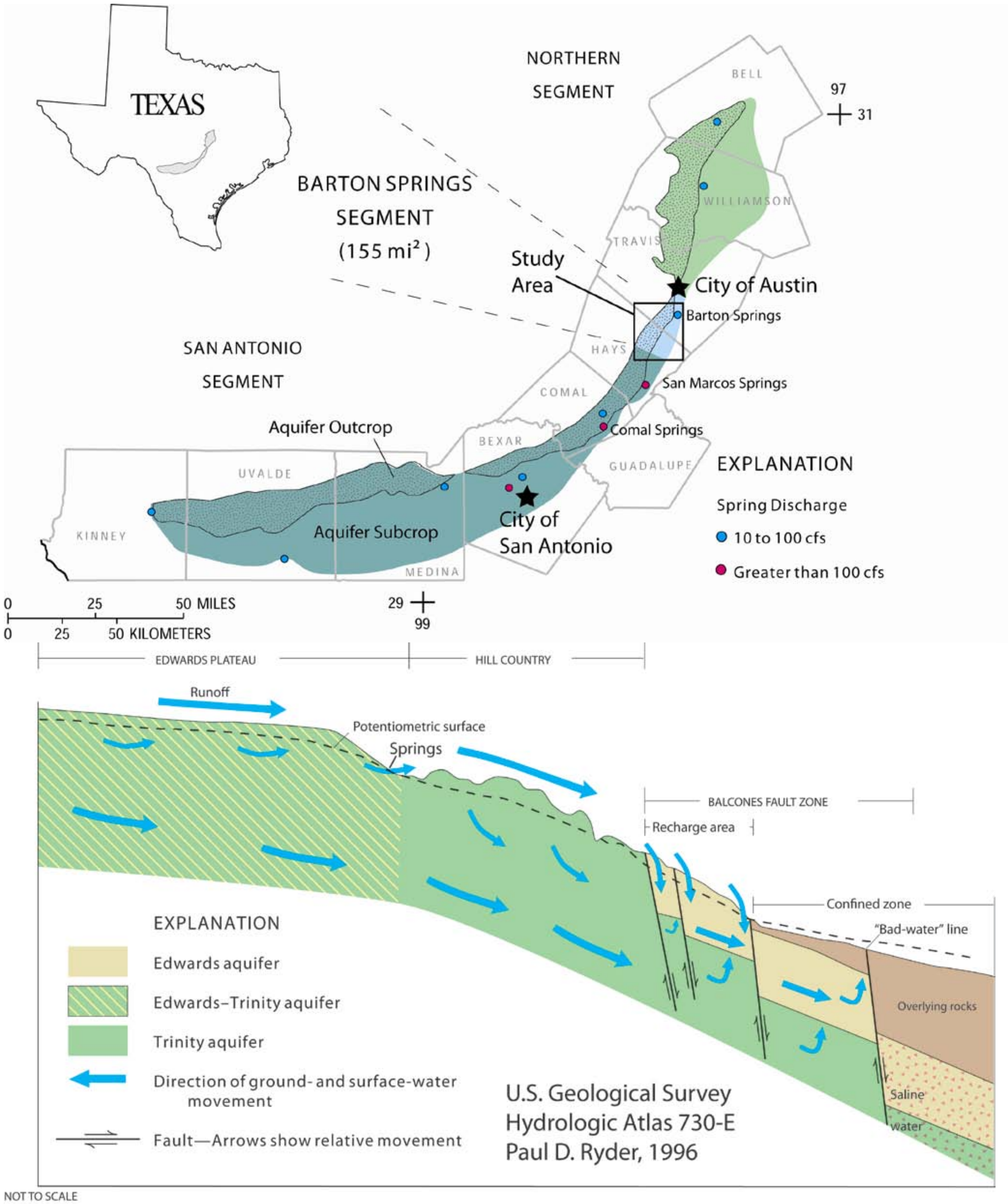
Geologic Map



Regional Stratigraphic Column

Era	Period		Provincial Series	Provincial Stage	Stratigraphic unit	Hydrostratigraphy	
Mesozoic	Cretaceous	upper	Gulfian	Navorroan	Navarro Group	Confining Units	
				Tayloran	Taylor Group		
				Austinian	Austin Group		
				Eaglefordian	Eagle Ford		
			Comanchean	Washitan	Buda Limestone		
					Del Rio Clay		
		lower			Georgetown Formation	Edwards Aquifer	
					Edwards Group: Person Formation		
				Fredericksburgian	Edwards Group: Kainer Formation		
				Trinitian	upper Glen Rose	upper	Trinity Aquifer
					lower Glen Rose	middle	
					Pearsall Fm.: Hensel Sand Mbr (Bexar Shale Mbr)		
					Pearsall Fm.: Cow Creek Mbr		
					Pearsall Fm.: Hammett Shale Mbr (Pine Island Shale Mbr)	confining unit	
					Sligo Fm	lower	
					Sycamore (Hosston) Fm		
Paleozoic					Undifferentiated Paleozoic Rocks	Paleozoic aquifers	

Modified from Barker and Ardis (1996).



Modified from Maclay, R.W., and Small, T.A., 1986, Carbonate geology and hydrology of the Edwards aquifer in the San Antonio area, Texas: Texas Water Development Board Report 296, 90 p.

Stop 1a: Multiport Monitor Well

Brian A. Smith, Ph.D., P.G. and Brian B. Hunt, P.G.,
Barton Springs/Edwards Aquifer Conservation District

To monitor horizontal and vertical flow of water recharging the aquifer through Antioch Cave, a multiport monitor well was installed about 1,700 ft (0.3 mi) east of Antioch Cave. The installation of the multiport monitor well at Antioch has provided a means for characterization of pathways within the aquifer. Movement of water recharged through the Antioch BMP and the nonpoint source pollutants in the aquifer will be monitored in discrete zones within a single monitor well that is completed with multiple monitoring zones.

The multiport well system installed at the site is manufactured by Westbay Instruments of Vancouver, Canada, a Schlumberger company. A similar well was installed by the District at Ruby Ranch about 4 miles west of Antioch in 2008. This well, with 14 monitor zones, was designed to monitor groundwater in the lower units of the Edwards Aquifer and the Upper and Middle Trinity Aquifers. With these types of wells, almost any number of monitoring zones can be installed in a well. Monitoring zones are separated by packers that seal off the annular space between the borehole wall and the well casing (see Figure on next page). Specialized (measurement) ports allow for access to the aquifer for sampling, water-level (pressure) measurements, and aquifer tests. Groundwater samples collected from each zone are representative of the groundwater in the aquifer between the packers. Water-level data from the zones can give an indication of potential direction of vertical movement of water within the aquifer. Aquifer tests, such as slug tests, can be conducted through the pumping ports to identify and characterize zones of higher permeability through which groundwater is more likely to flow. Data from such a well at Antioch will provide needed information about how nonpoint source pollutants are moving through the Edwards aquifer and how they might impact water-supply wells and Barton Springs. Sampling of the well will be conducted in conjunction with recharge events to see how the sediments and contaminants in the surface water are transmitted through the aquifer. This well is also providing insight into the hydraulic relationships between the Edwards and the various Trinity units.

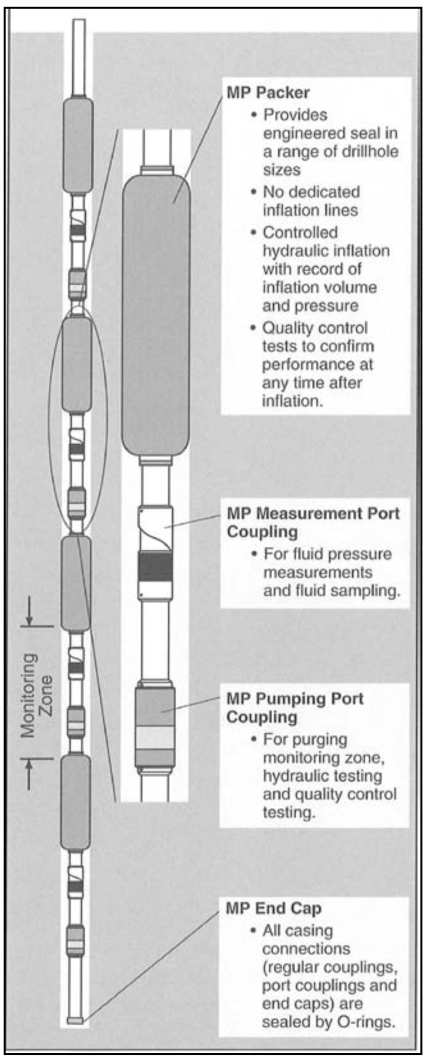
Installation of Multiport Well

The procedure for installing this well was to drill a 5 ¼ -inch borehole to a depth of about 1,375 ft using air-rotary drilling techniques. Small amounts of water and drilling foam were used to help circulate drill cuttings to the surface. Eight-inch diameter surface casing was installed to a depth of about 115 ft to seal off the Buda and Del Rio Formations from the monitor zones of the Edwards below. Geophysical logs were run in the completed borehole. A gamma log was used to determine approximate contacts of the various geologic units. A caliper log was run to measure the diameter of the borehole so that packers could be placed where there are no cavities that would interfere with packer inflation. A video log was run on the borehole for lithologic and structural (fracture) inspection for packer placement. Once the geophysical logs are run and interpreted, the well is designed by laying out all of the components of the Westbay® multiport well on paper or on a computer. The main components of the system are packers, measurement ports, pumping ports, end caps, 2-ft, 5-ft, and 10-ft sections of 1 7/8–inch OD diameter PVC casing, regular couplings, and magnetic location collars. Each zone consists of a packer at the top and bottom of the zone, one measurement port, one pumping port, a magnetic collar placed 2 ft below the measurement port, and regular couplings to connect the sections of PVC casing. Measurement and pumping ports also serve to connect sections of PVC casing. Zones may be as thin as 5 ft or as thick as hundreds of feet. Packers are set at or near the contacts between desired monitoring zones. These zones typically correspond to the hydrogeologic zones encountered in the well. The measurement ports can be placed anywhere between the packers, but are usually placed about halfway between the packers. A pumping port is typically placed 10 ft below the measurement port. Once the well is designed, the installation process follows these steps:

- Visually inspect and lay out the Westbay® system casing components in sequence (Figure 2-3).
- Record the serial numbers for each packer, measurement port, and pumping port.
- Assemble each casing joint and test the hydraulic seals.
- Lower the casing into the borehole.
- Test the hydraulic integrity of the entire casing string.
- Inflate the packers sequentially from bottom to top, recording the inflation pressure and volume of water used for each packer.
- Measure fluid pressures at each measurement port to confirm proper operation and check the annular hydraulic seals between monitoring zones.

Once the last packer is inflated, a protective casing is placed at the well head plus a concrete pad and protective posts (Figure 2-4).

Drilling of the borehole began on July 26, 2010. By August 18, the borehole had been advanced to a depth of 1,017 ft, but problems with drilling a narrow diameter borehole to such a depth prevented any further drilling until a different set of equipment could be obtained. Using a string of narrow-diameter drill rods, drilling resumed on September 14. By September 16, the borehole had reached a depth of 1,375 ft. Geophysical logging of the borehole indicated that the borehole had reached the bottom of the Cow Creek Limestone, which was the target for the lowermost zone of the monitor well.



Schematic diagram of multiport monitor well components and construction. Diagram courtesy of Schlumberger Water Services, Inc.

Photograph of layout of multiport monitor well components prior to installation.

Photograph of the wellhead of the completed Antioch multiport monitor well during a sampling and water-level measurement event.

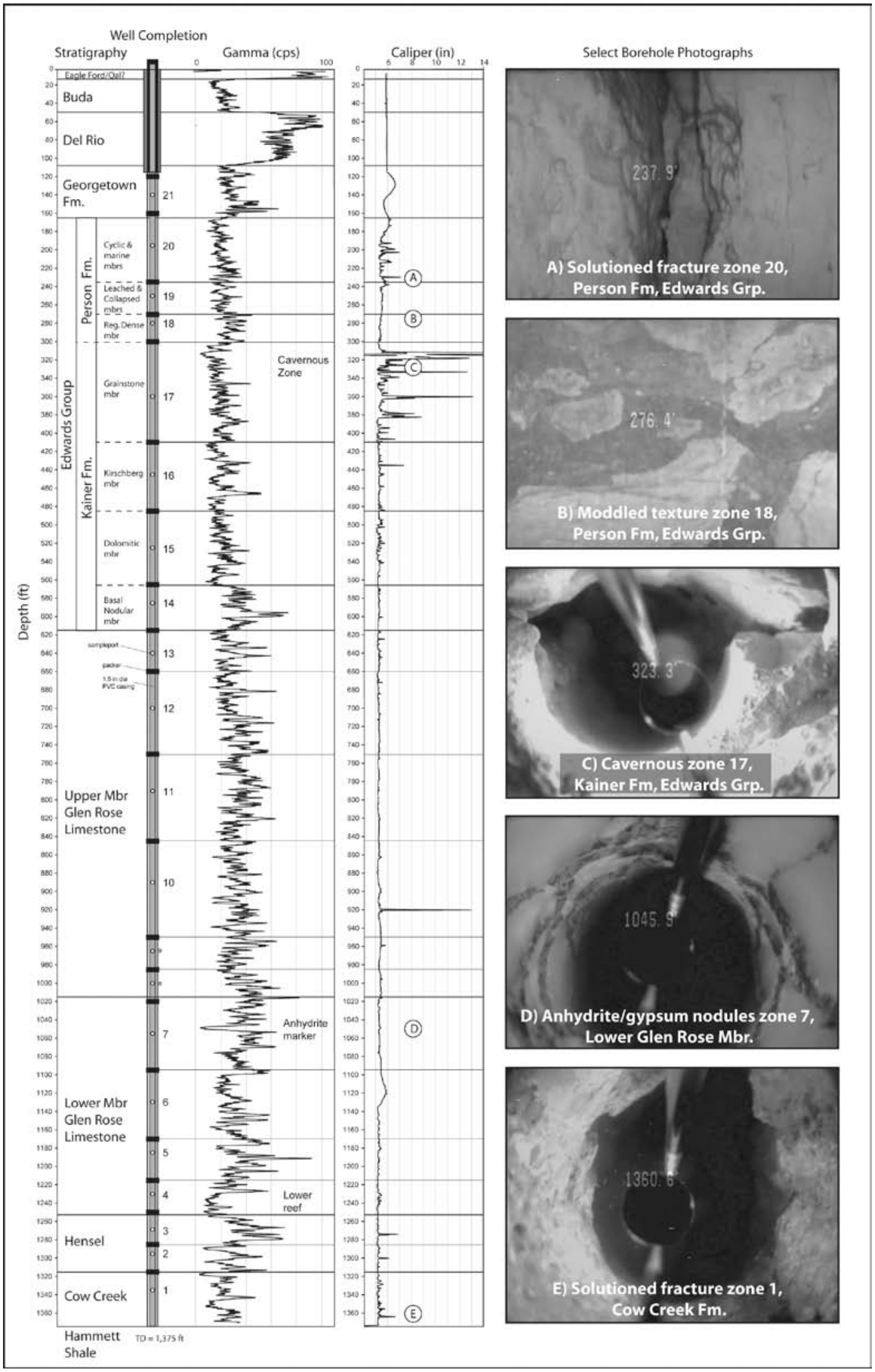


Diagram showing multiport monitor well construction, hydrogeologic units encountered in well, gamma and caliper logs, and photographs from the downhole video log.

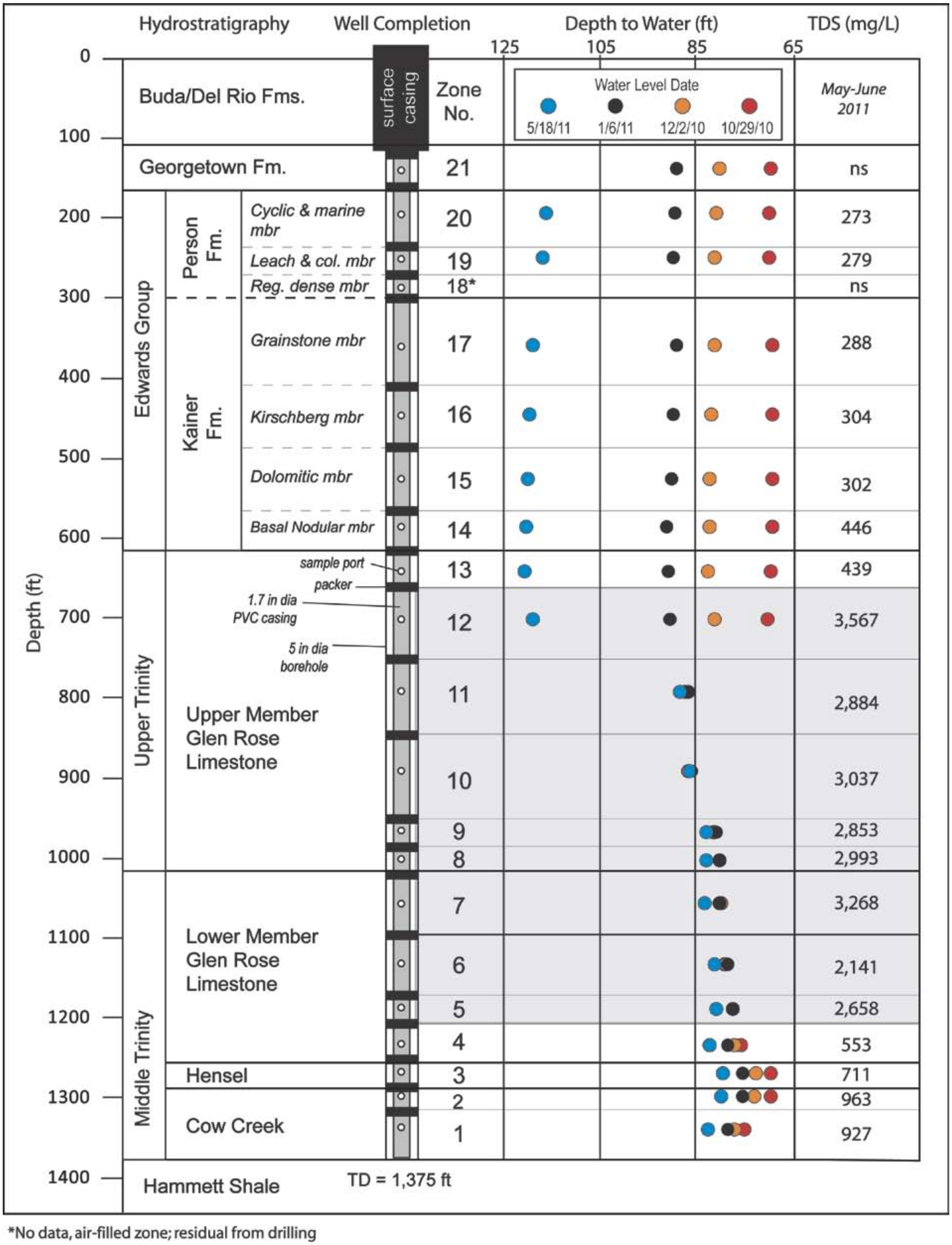


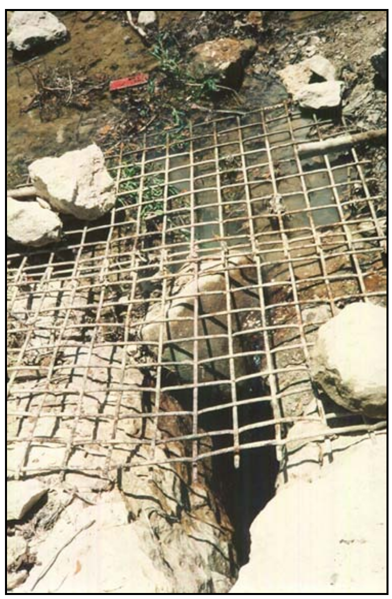
Diagram showing multiport monitor well construction, hydrogeologic units encountered in well, water-level results for five measurement events, and TDS values.

Stop 1b: Antioch Cave Recharge Enhancement Facility

Brian A. Smith, Ph.D., P.G. and Brian B. Hunt, P.G.
Barton Springs/Edwards Aquifer Conservation District

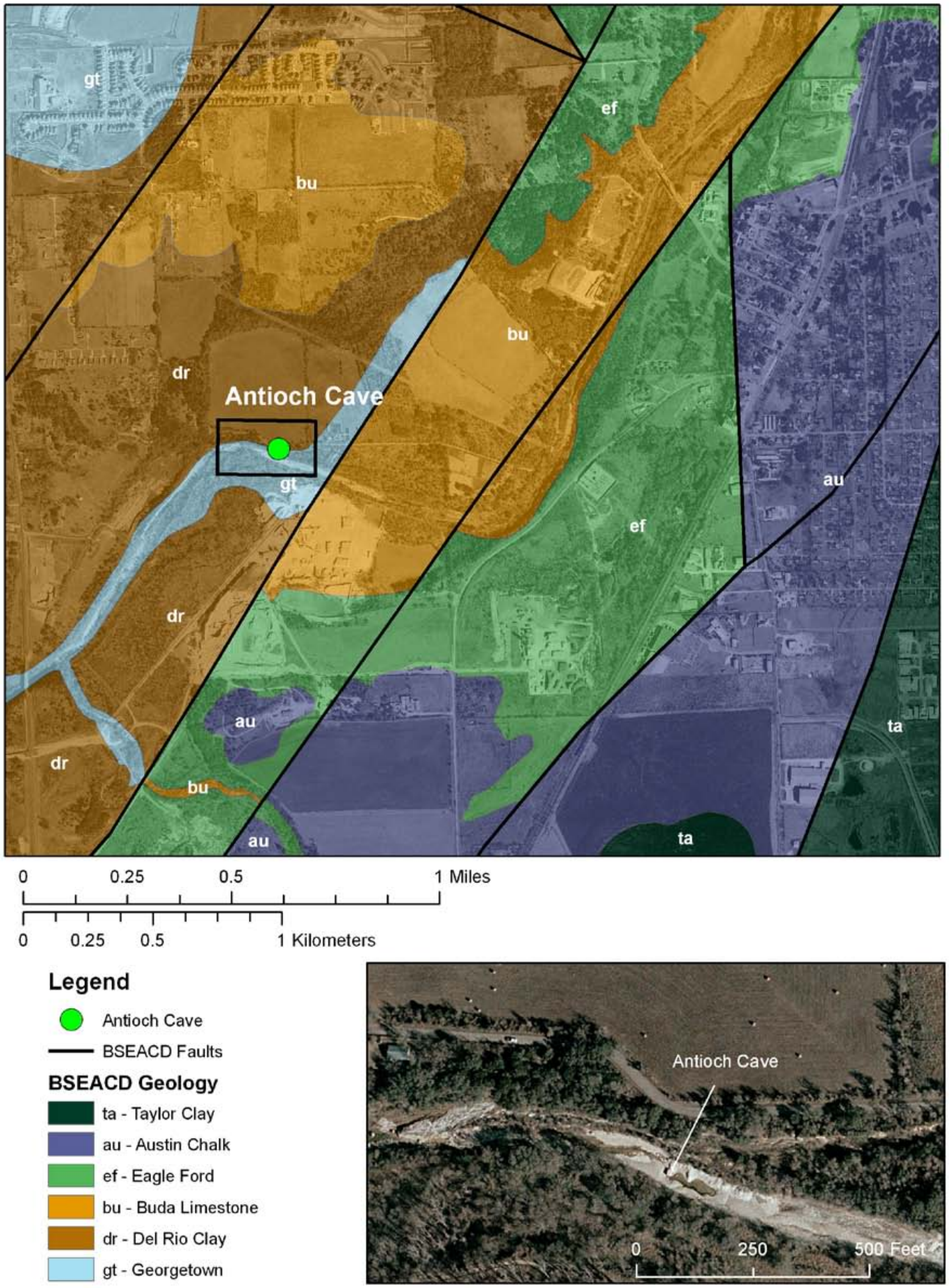
Quick Facts:

- Average recharge into cave in 1998 was 46 cfs (1,300 lps); largest capacity recharge feature in the Barton Springs segment
- Surface water catchment area: ~175 square miles
- Elevation: ~690 feet above sea level
- Site of the BSEACD's EPA and TCEQ-funded recharge enhancement project.
- Dye traced to Barton Springs in 7-8 days (17 miles away)



Photograph ca. 1996 showing recharge and the entrance to Antioch Cave before the BMP was constructed. The debris over the entrance and also sedimentation within the cave decrease the amount of recharge entering the cave. (Photograph from Fieseler, 1998).

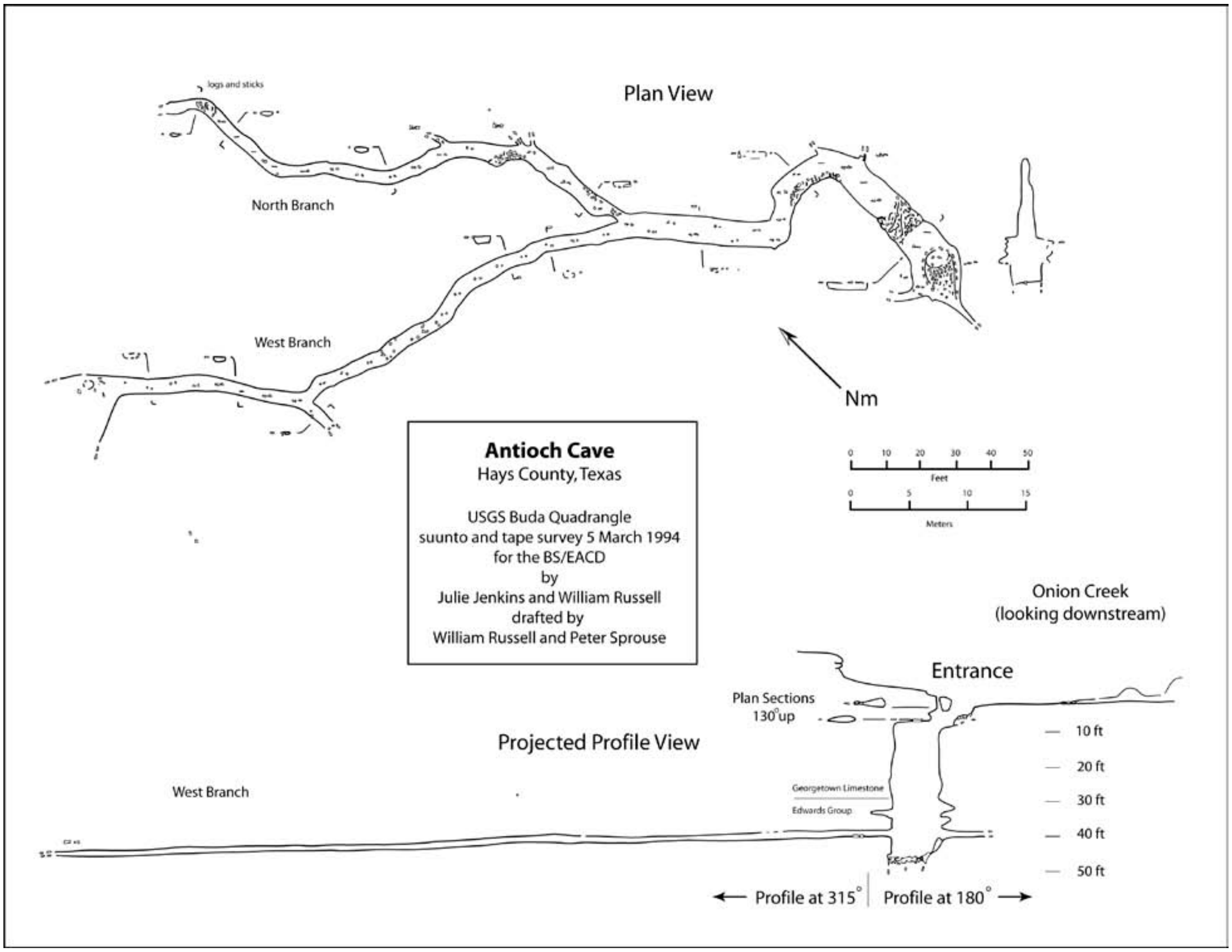
Geology of the Antioch Cave Area



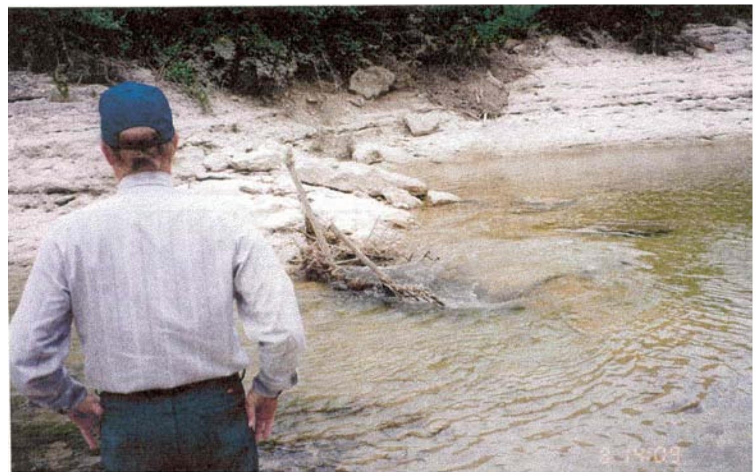
Abstract from report:
Onion Creek Recharge Project Northern Hays County, Texas

The presence of nonpoint source pollution in stormwater flowing in Onion Creek can have a direct impact on water quality in the Barton Springs segment of the Edwards Aquifer in Hays County, Texas. To address this concern, the Barton Springs/Edwards Aquifer Conservation District constructed a concrete vault over the entrance to Antioch Cave in the bed of Onion Creek in 1997. This structure was designed to prevent entry into the cave of contaminated stormwater by closure of a valve on the vault during storm events. The goals of the current project were to improve the efficiency of the system at Antioch by automating the operation of the valve and to install two water-quality monitoring systems on Onion Creek, one at Antioch and the other near the upstream end of the recharge zone. Results of water-quality sampling at Antioch indicate that the system is capable of significant reduction of nonpoint source pollution entering the aquifer through Antioch Cave. During the course of this project, approximately 2,436 lbs of nitrogen from nitrate/nitrite, 295 lbs of total phosphorus, and 190,480 lbs of sediment were prevented from entering Antioch Cave. To monitor the potential movement of nonpoint source pollution in the aquifer, a multiport monitor well was installed near Antioch Cave. With this well, groundwater samples can be collected from multiple vertical zones within the Edwards and Trinity Aquifers. Initial results from this well indicate that there is little, if any, hydraulic connection between the Edwards and Trinity Aquifers. Future studies will determine the degree of hydraulic connection between Antioch Cave and the Edwards zones in the multiport monitor well.

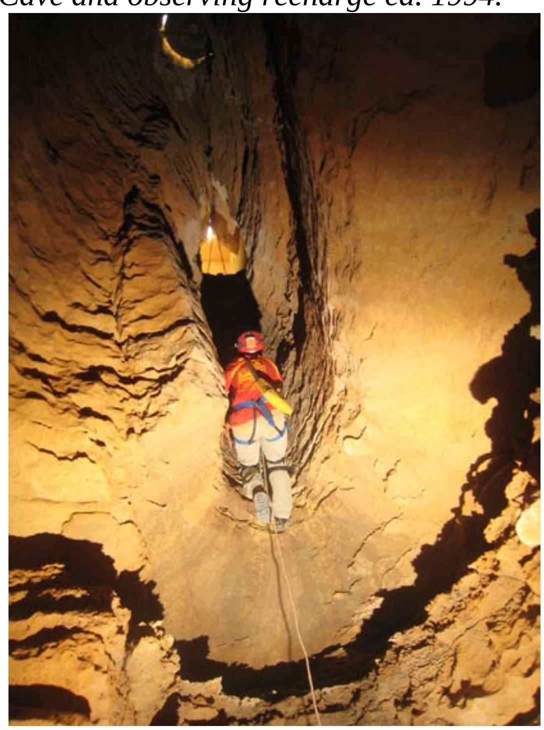
source:
http://www.bseacd.org/uploads/319h%20Onion%20Creek%20Final%20Report%208_15_11_web.pdf



Map of Antioch Cave showing plan and profile views.

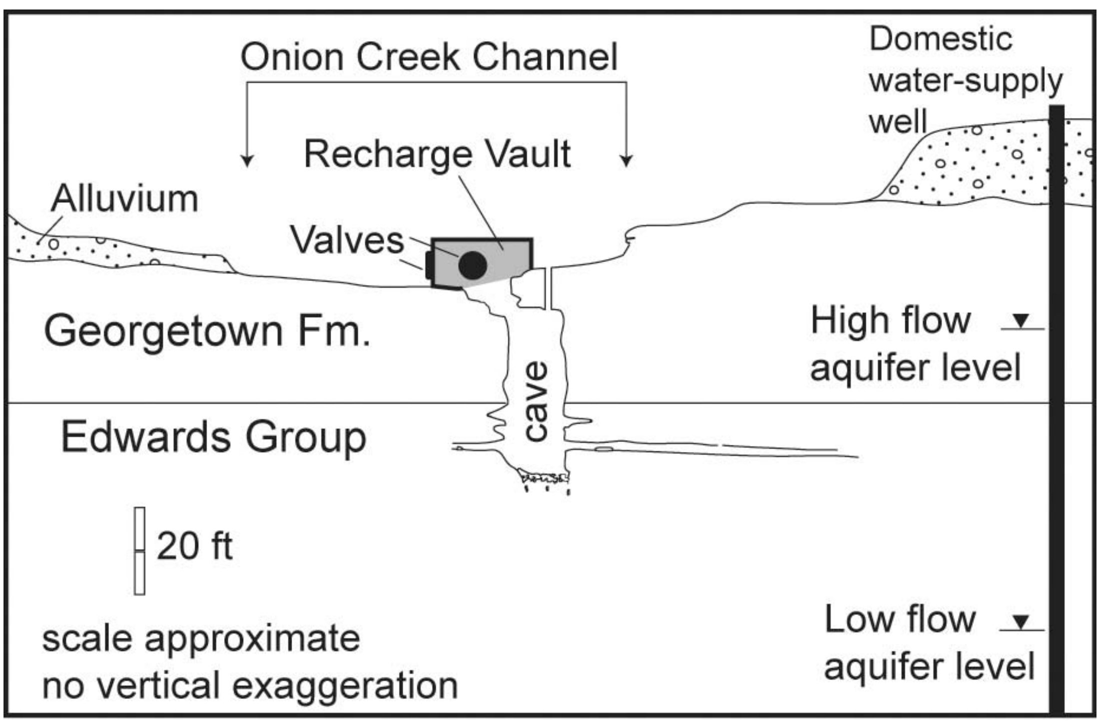


Ron Fieseler entering Antioch Cave and observing recharge ca. 1994.

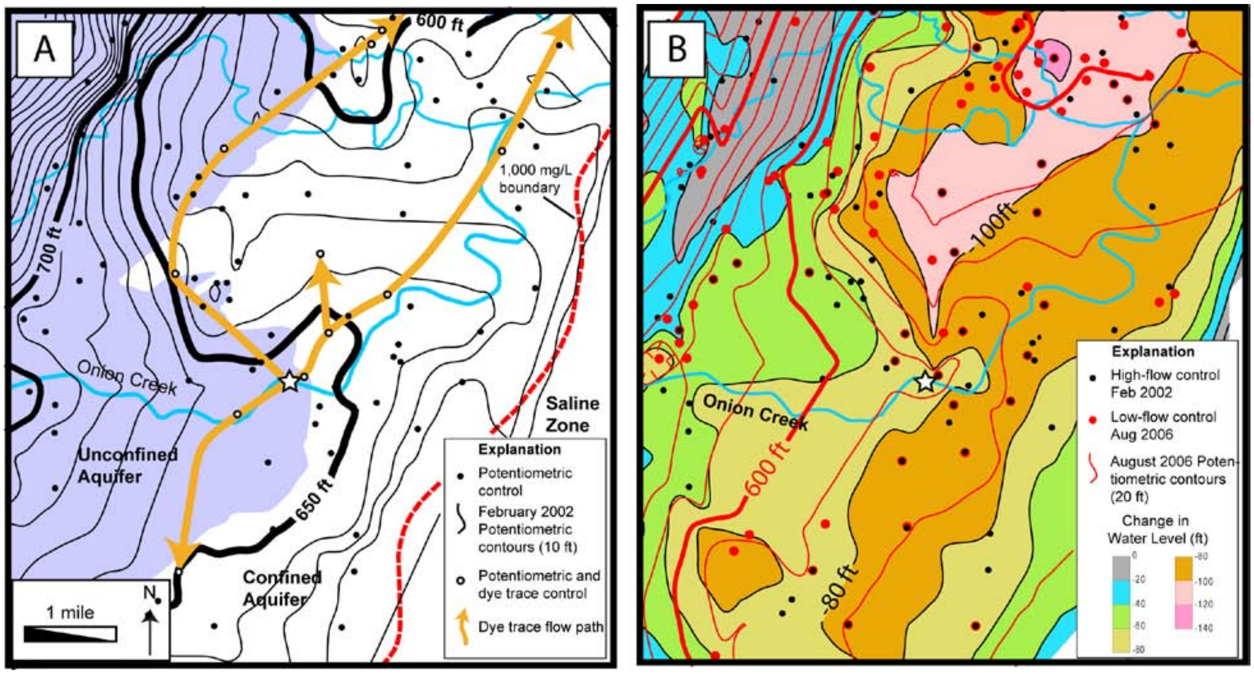


Caver rappelling into entrance pit of Antioch Cave. Vault and air vent are visible.
Photo by Peter Sprouse

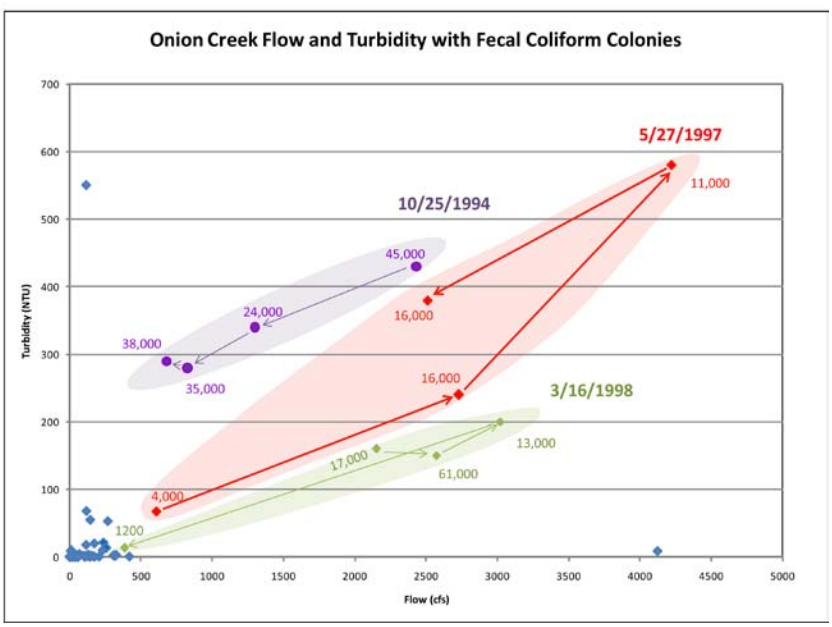
Photograph ca. 1997 showing the near-finished BMP vault over Antioch Cave; circular openings are 36 inches in diameter. (Photograph from Fieseler, 1998).



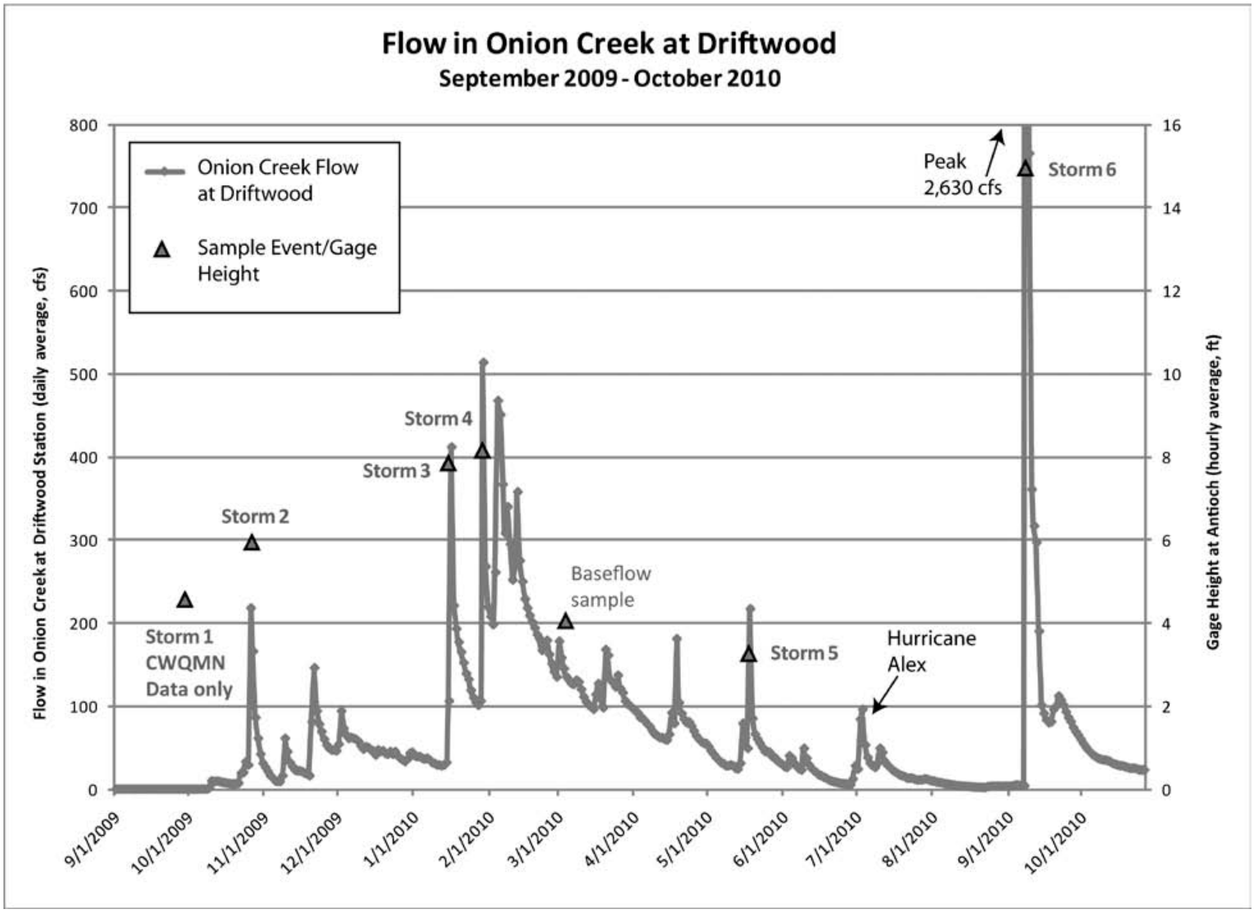
Schematic cross section across Onion Creek and Antioch BMP looking upstream.



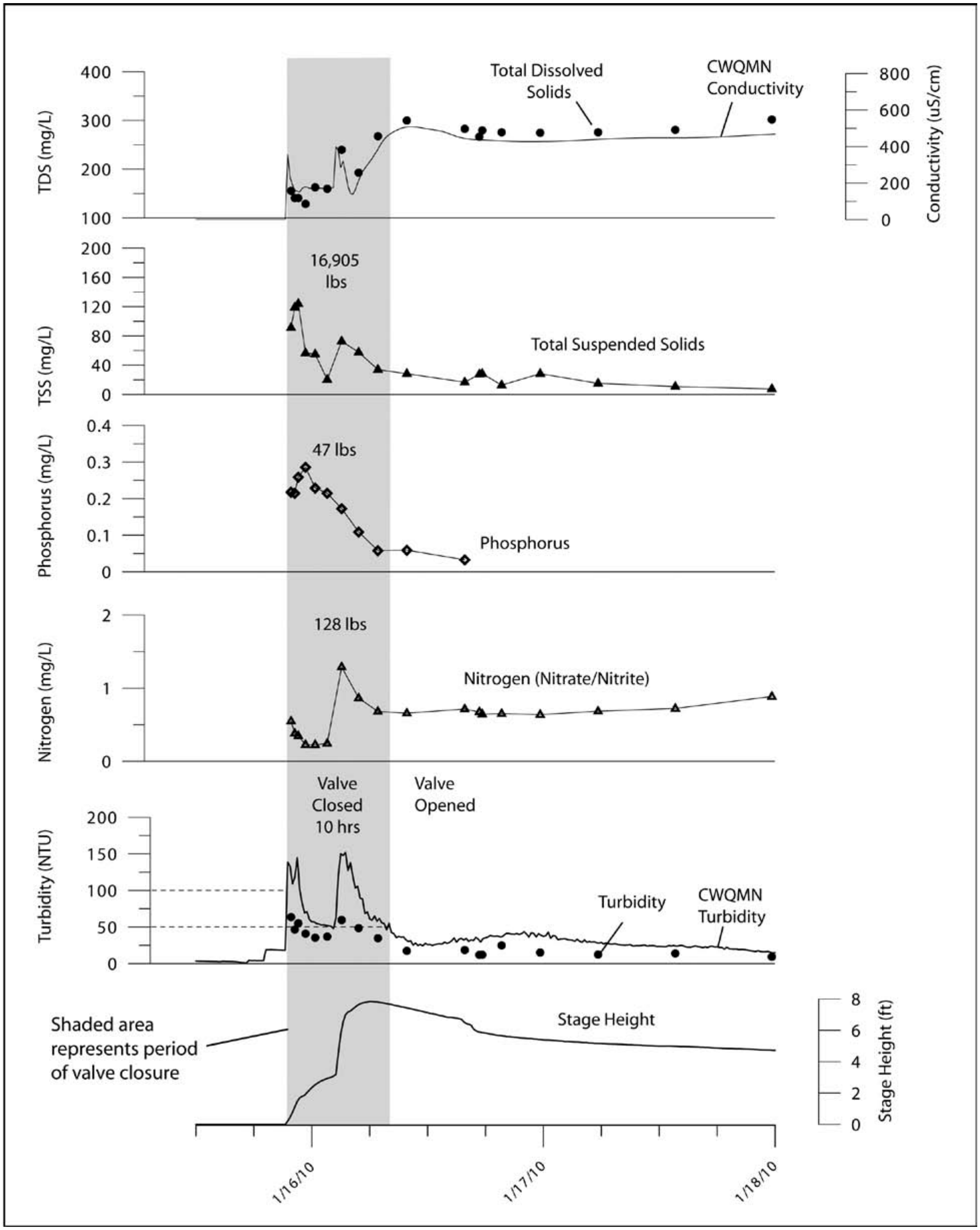
A) Regional potentiometric map along Onion Creek during high-flow conditions (February 2002). The 650-ft contour illustrates the mounding effect due to discrete recharge from Antioch Cave. Lines with arrows indicate direction of groundwater flow from dye-trace studies. B) Map of the change in water levels from high (February 2002) to low-flow conditions (August 2006).



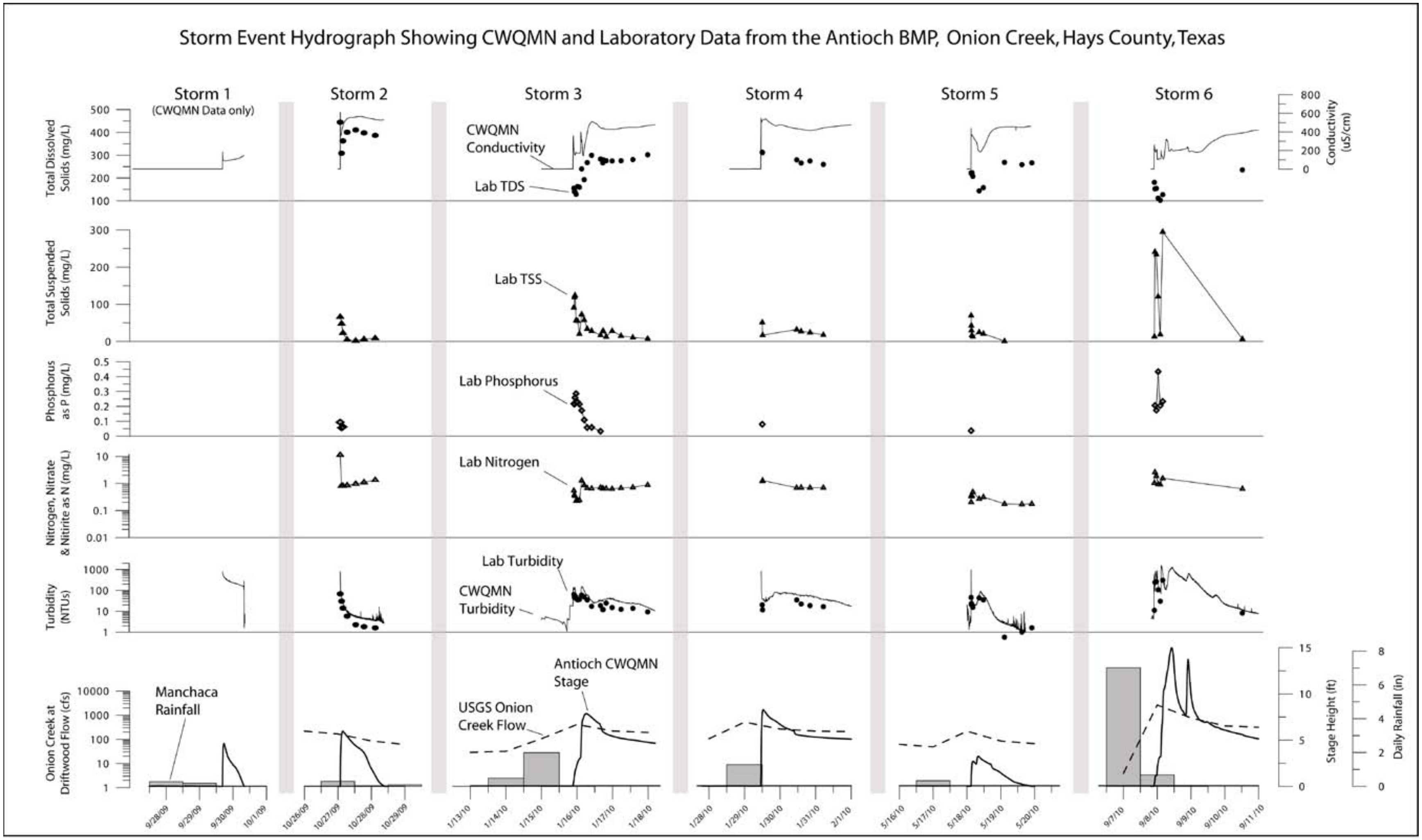
Flow in Onion Creek at the USGS Driftwood station showing turbidity plotted against flow plus bacteria (number of fecal coliform colonies) for three storm events. Shaded areas correspond to a particular storm event. Arrows represent the time sequence of sample collection within a storm event. Data from the USGS.



Storm events sampled for this project are shown superimposed on hydrograph of Onion Creek at the USGS Driftwood station from August 2009 to October 2010. The Driftwood station is about 13 miles upstream of the Antioch Cave site.



CWQMN and laboratory analytical data for Storm Event 3.



*Results below detection levels are not shown.

Antioch CWQMN data for six storm events and laboratory analytical results of surface-water samples collected at the Antioch BMP from five storm events.

Mass of contaminant reduction from operation of Antioch BMP for five storm events.

Storm Event	Start (NTU>100)	End (NTU<50)	Duration (days)	Duration (hours)	Average Peak Storm Values[2] (mg/L) N[1]	P[1]	TSS	Contaminant Reduction[3] in **lbs** (kg) N[1]	P[1]	TSS
1	Samples not collected for laboratory analysis									
2	10/27/09 1:41	10/27/09 2:27	0.03	0.8	6.16	0.075	57.5	**106** (48)	**1.3** (0.6)	**990** (449)
3	1/15/10 21:30	1/16/10 8:15	0.45	10.7	0.53	0.195	70.0	**128** (58)	**47** (21)	**16,905** (7,666)
4	1/29/10 11:15	1/31/10 0:30	1.55	37.3	0.92	0.02	30.2	**770** (349)	**17** (7.6)	**25,271** (11,461)
5	5/18/10 2:56	5/18/10 12:31	0.40	9.6	0.33	0.005	31.2	**71** (32)	**1.1** (0.5)	**6,717** (3,046)
6	9/9/10 14:26	9/7/10 21:46	1.69	40.7	1.49	0.25	153.9	**1,361** (617)	**228** (104)	**140,597** (63,763)
		Total Duration	**4.1**	**99.0**			**Totals (lbs)**	**2,436**	**295**	**190,480**
							Totals (kg)	1,105	134	86,385

Notes:
1- N is nitrogen from nitrate and nitrite; P is total phosphorus.
2- For period during which the valve was closed.
3- Mass of contaminants not entering Antioch Cave while valves are closed.

Stop 1c: Geophysics

Mustafa Saribudak, Ph.D.
EGA, Houston Texas

Resistivity Imaging (AGI SuperSting R1/Swift System)

Resistivity imaging is a survey technique that aims to build up a picture of the electrical properties of the subsurface by passing an electrical current along electrodes and measuring the associated voltages. This technique has been used widely in determining karst features, such as voids, and subsurface structures, such as faults and fractures.

In this study, we used AGI's SuperSting R1 resistivity meter with dipole-dipole resistivity technique, which is more sensitive to horizontal changes in the subsurface, and provides a 2-D electrical image of the near-surface geology**.**

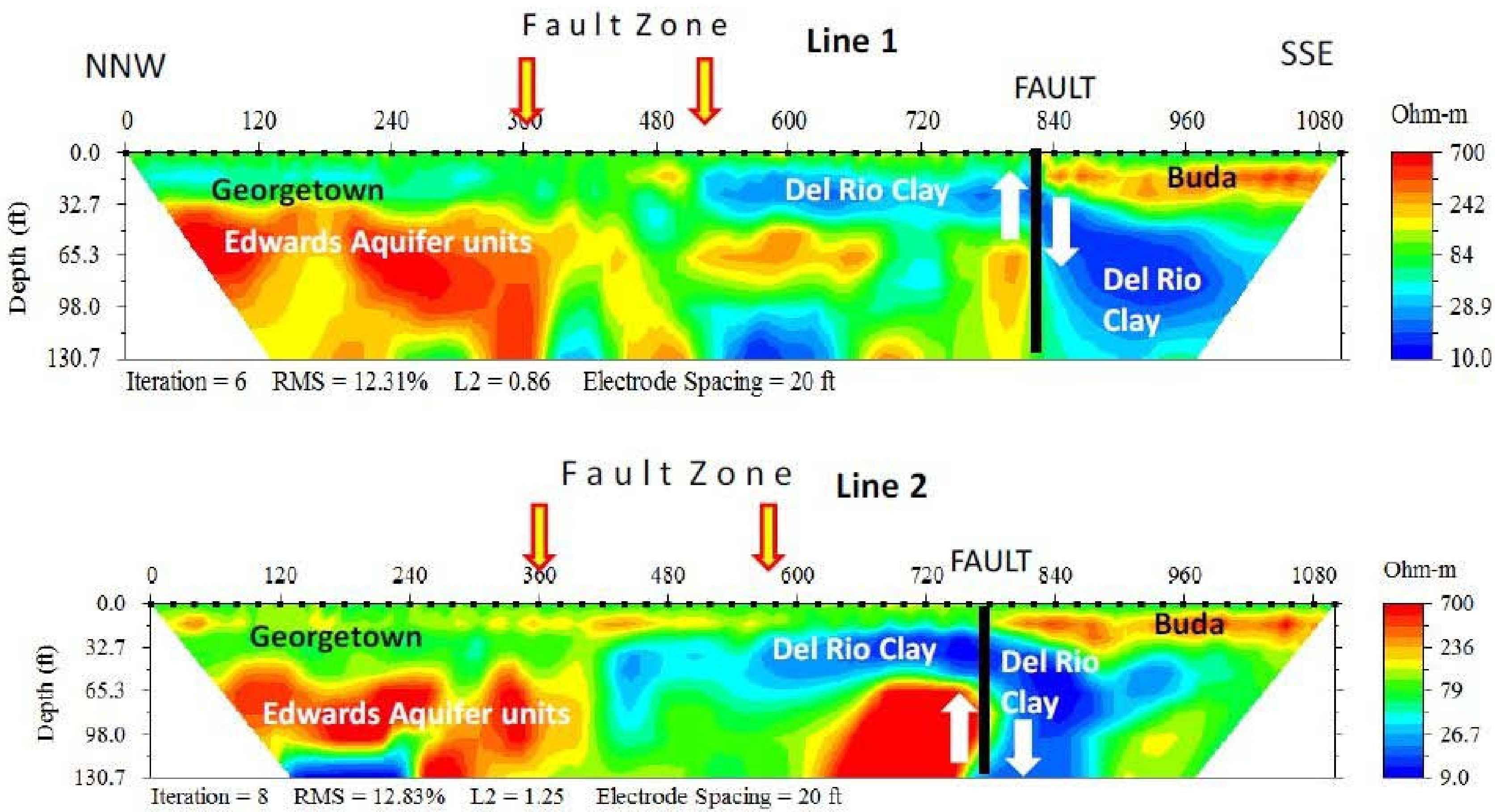
We collected roll-along resistivity data across the faults. After the initial section of resistivity data was collected, the first cable of 14 electrodes was moved ahead of the survey line. This process was continued until all data along the desired length were collected. The data from the roll along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

Natural Potential

Natural electrical (NP) currents occur everywhere in the subsurface. In seepage or cave investigations we are concerned with the unchanging or slowly varying direct currents (d.c.) 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 electrodes and a sensitive measuring device (i.e. a voltmeter). It should be noted that water movement should be present within or surrounding a cave in order to determine a void or cave location. Positive and negative NP values are attributed to changes in the flow conditions. The source of NP anomalies can be also due to changes in topography, 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.
There is no commercially available NP device in the geophysical market. For this reason, we fabricated a NP system to use in this study. The NP unit consists of a voltmeter, copper-sulfide electrodes, and 2500 feet of wire on a reel.

Field Geologic Map and Geophysical Transects, Antioch Cave Property, Hays County, Texas

BSEACD 8.19.11



Resistivity data along Line 1 and Line 2. The resistivity data are interpreted based on the geological information.

Figure 6. Correlation of resistivity and NP data along Line 1.

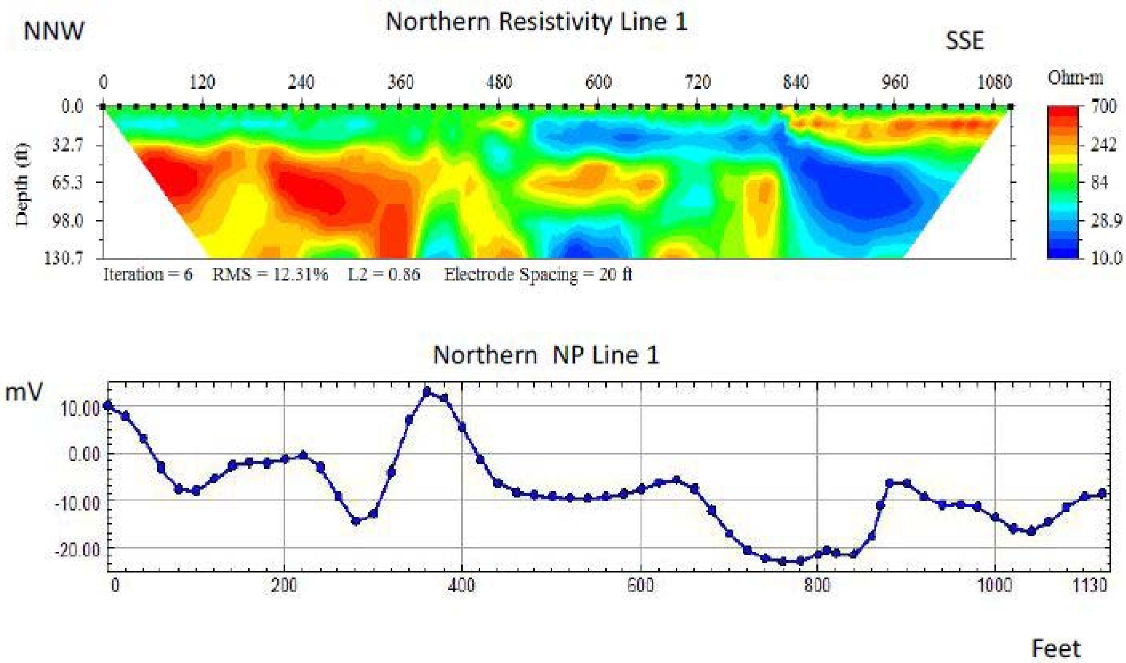
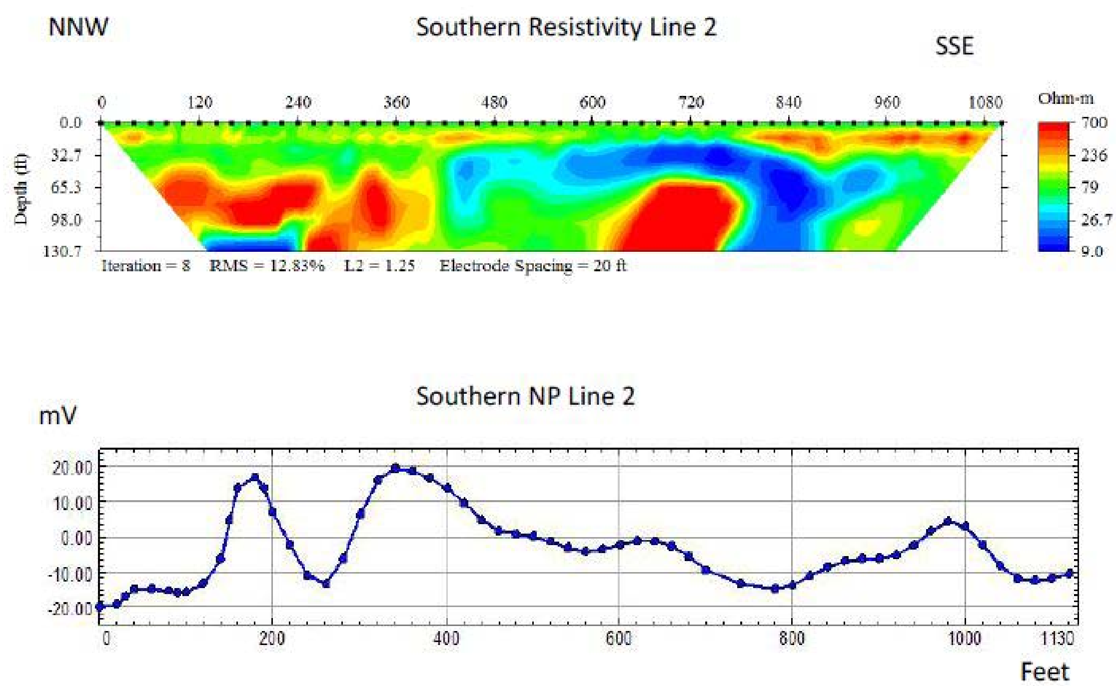


Figure 7. Correlation of resistivity and NP data along Line 2.



Stop 2: Barton Springs

David Johns, P.G., and Nico Hauwert, Ph.D., P.G.
City of Austin Watershed Protection and Development Review

2a. Barton Springs Overview (David)

- BS pool general
- Management of pool for swimmers and endangered species
- Pool restoration, natural and human infrastructure
- BS discharge, daily and annual averages
- Jurisdiction of recharge and contributing zone
- BS chemical trends

2b. BSEA Tracing (Nico)

- Overall tracing summary
- Spring source areas
- Significance of Blanco River flows
- Urban areas and karst sensitivity

2c. Case Studies in Development over Karst (David and Nico)

- Karst surveys for development
- Karst influence on building designs
- Leaking infrastructure
- Stormwater treatment
- Diversion of stormwater runoff into karst features

2d. Salamander show and tell (David)

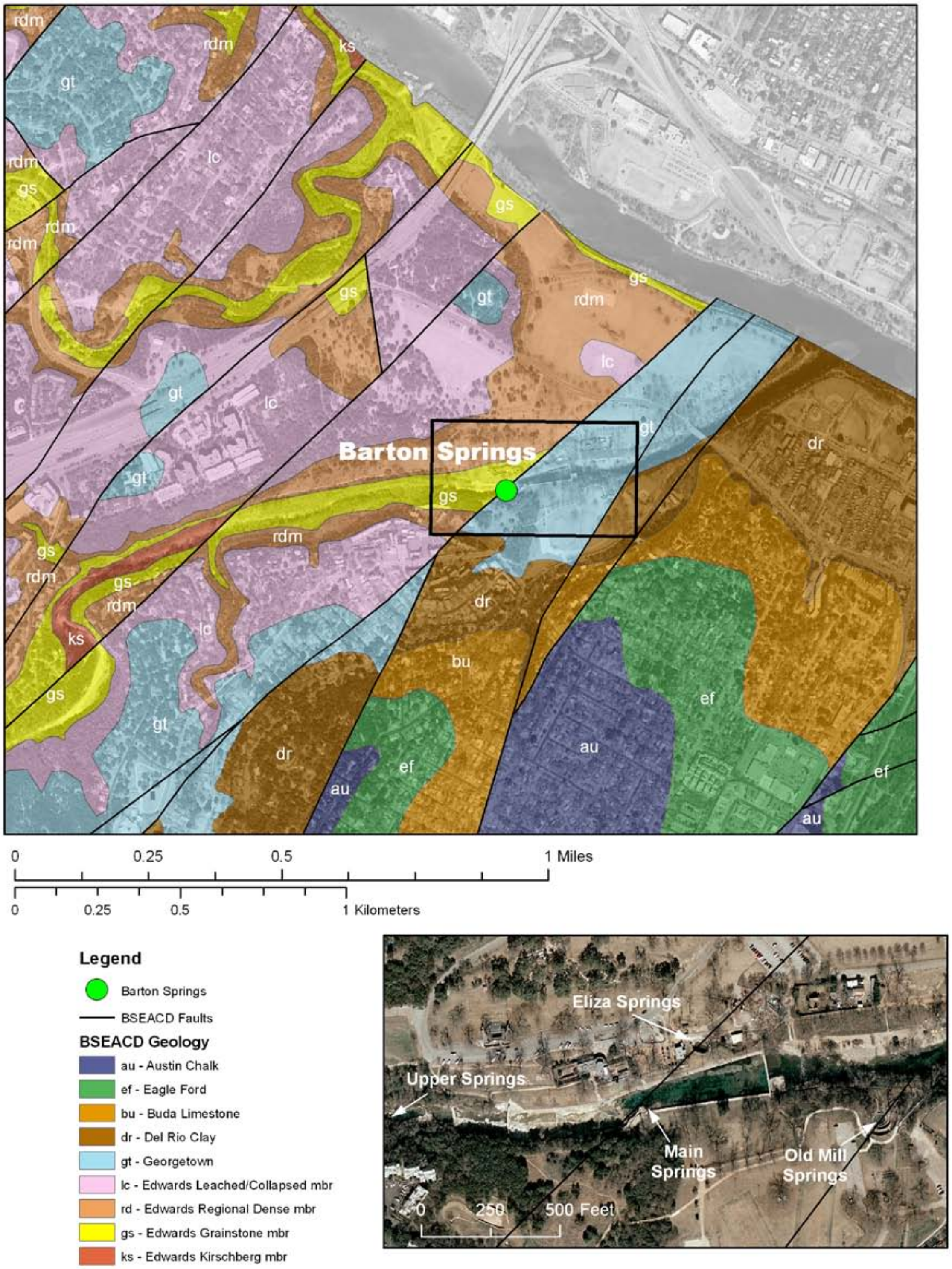
- Visit Eliza Spring to view salamanders

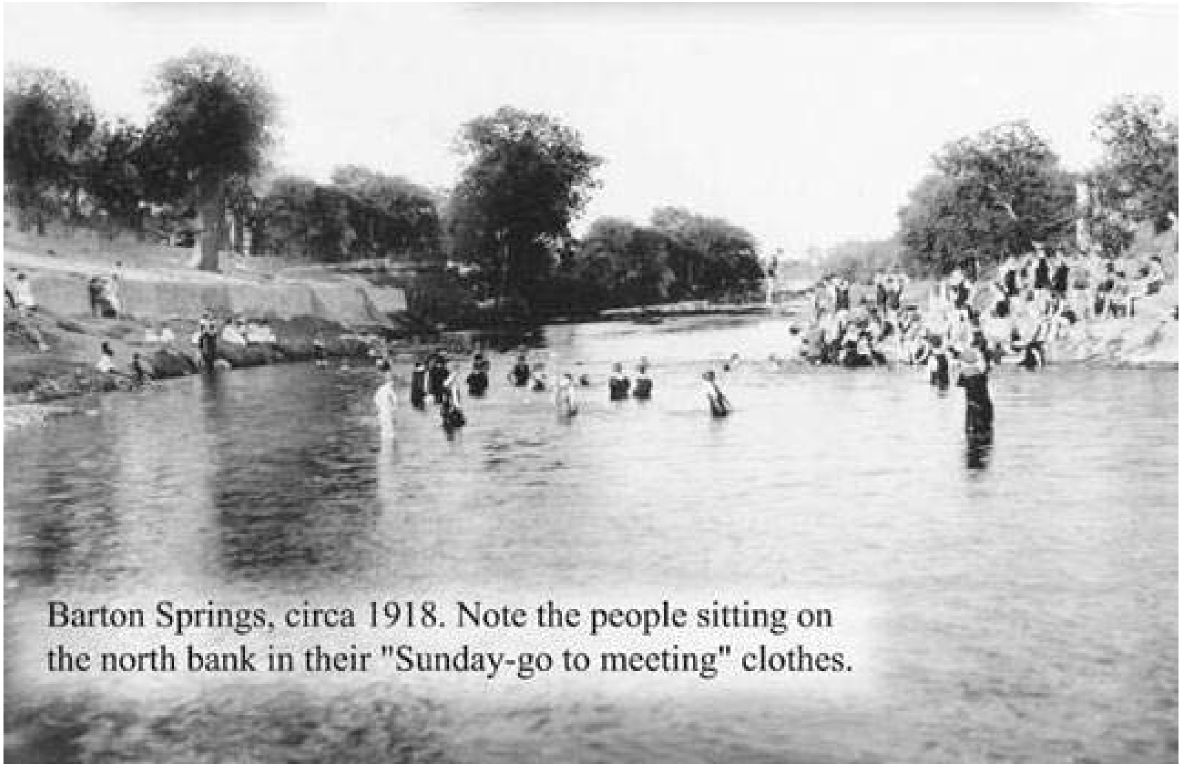
2e. Geophysics (Mustafa)

Quick Facts:

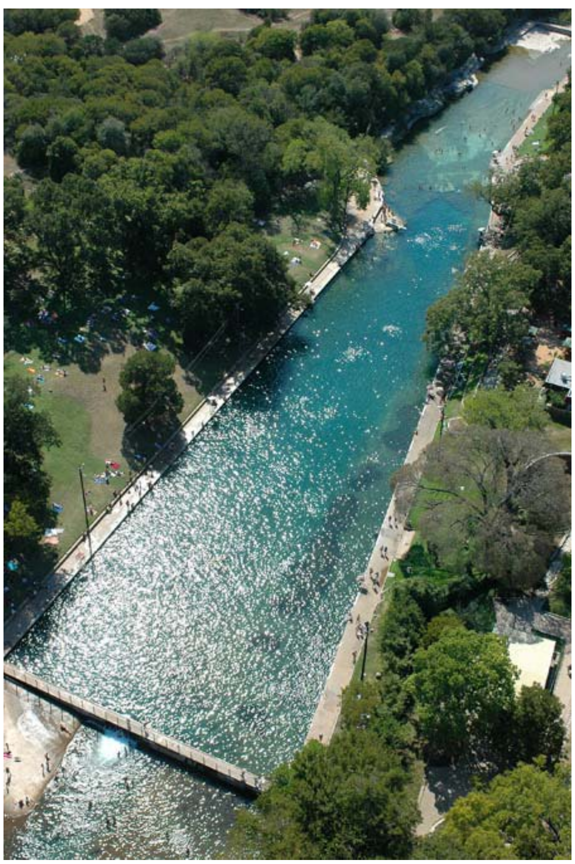
- 4th largest spring system in Texas
- Water temperature: 68°F (22°C)
- Mean discharge: 53 cfs (1,500 lps)
- Lowest recorded discharge: 9.8 cfs (278 lps) on March 29, 1956
- Elevation: 462 feet above sea level
- Known habit of the federally listed Barton Springs salamander (*Eurycea*

Geology of the Barton Springs Area





Barton Springs, circa 1918. Note the people sitting on the north bank in their "Sunday-go to meeting" clothes.



Aerial view of Barton Springs Pool.

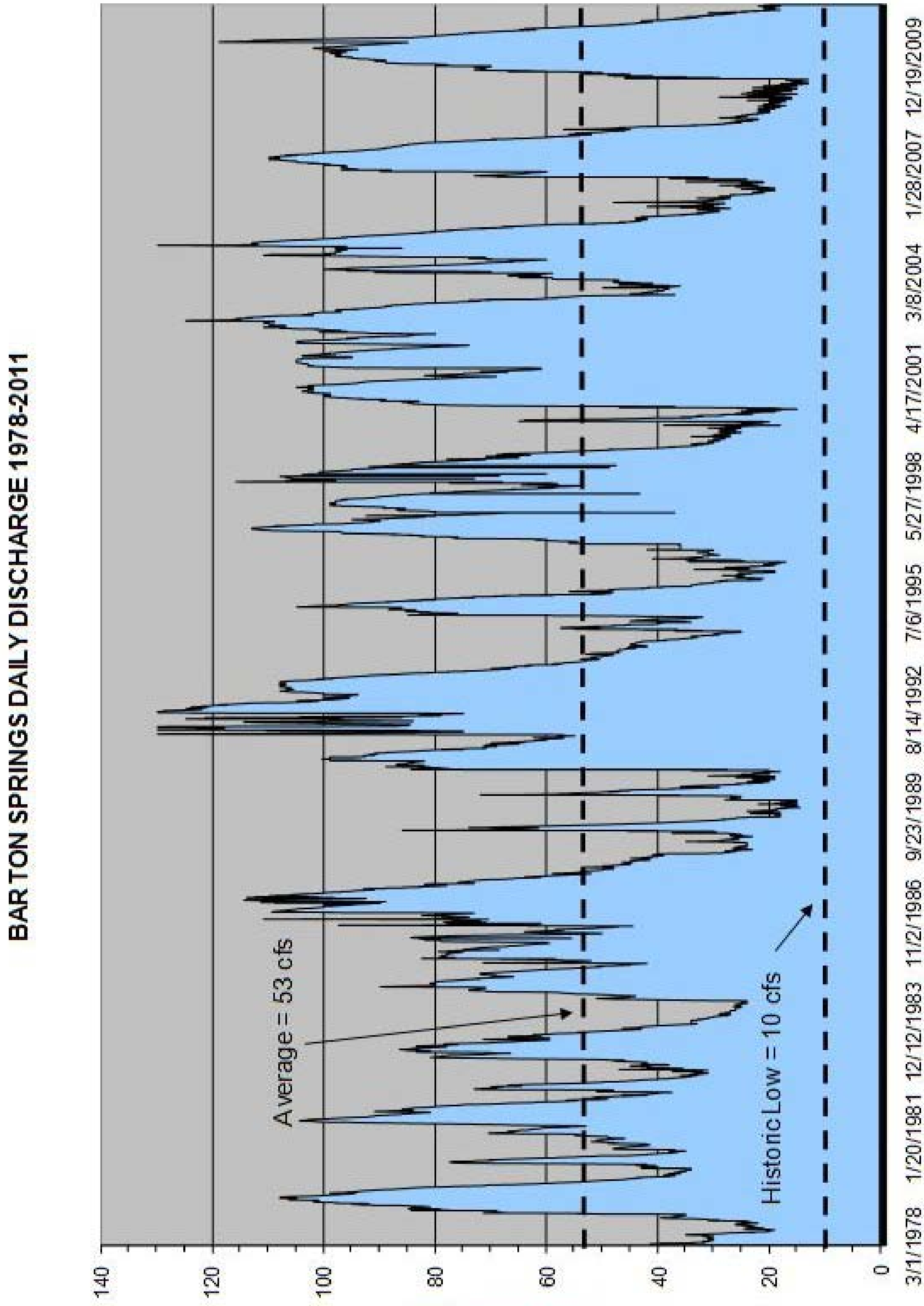
View of pool during cleaning. Barton Springs fault is clearly visible in this photo (see line marking trend)

Summary of temporal trends in water chemistry at Barton Springs.

Increasing	Decreasing
Alkalinity	Total Kjeldahl Nitrogen as N
Hardness, Non-Carbonate Hardness	Dissolved Oxygen
Calcium	pH
Fluoride	
Magnesium	
Potassium	
Sodium	
Sulfate	
Strontium	
Silica	
Conductivity, TDS	
Fecal coliform bacteria	
Nitrate/Nitrite as N	
Water temperature	

source:

Update of Barton Springs Water Quality Temporal Trend Analysis—2005.
Chris Herrington, Scott Hiers, P.G. and David Johns, P.G.
Water Resource Evaluation Section, Environmental Resource Management Division,
Watershed Protection & Development Review Department, City of Austin. SR-05-09. August 2005


BARTON SPRINGS DAILY DISCHARGE 1978-2011
DISCHARGE (cfs)
Average = 53 cfs
Historic Low = 10 cfs
0
20
40
60
80
100
120
140
3/1/1978
1/20/1981
12/12/1983
11/2/1986
9/23/1989
8/14/1992
7/6/1995
5/27/1998
4/17/2001
3/8/2004
1/28/2007
12/19/2009

Sources of Flow to Barton Springs

Nico Hauwert, Ph.D., P.G., City of Austin Watershed Protection

Barton Springs is an anomalous spring. Four clusters of spring outlets (Main Barton, Eliza, Old Mill, Upper Barton Springs) discharge from the karstic Edwards Group and overlying Georgetown limestone. How are these spring outlets related? How can a relatively uncontaminated karst spring exist in the middle of a large city? How does the springflow sustain during droughts?

In the 1800s geologists looked at the Edwards Aquifer as a conduit dominated flow system, based on widespread observation of caves, disappearing streams, and aquatic vertebrate aquifer life. By the 1980's the Edwards Aquifer was described as a diffuse dominated system with some conduits, in part because of sustained springflow and water level recession. Assuming the aquifer was a porous media system, it was calculated that recharge required more than 3 years to reach Barton Springs from Onion Creek. (Alexander, 1990). Initial estimates of creek recharge sources and intervening recharge were based on creek-flow loss data prior to delineation of the groundwater sources using groundwater tracing, the world-wide standard tool for karst investigation. The resulting estimates that intervening recharge areas contributed only 15% of Barton Springs flow and pumpage (Slade et al., 1986) led to calculations that less than 1% (alternate interpretations could indicate 2.6%) of rainfall directly infiltrated intervening recharge areas (Woodruff, 1984) No other karst aquifer worldwide has been attributed with such poor infiltration, less than 7% infiltration from rainfall estimated for the Trinity Aquifer or even less than 1% of rainfall estimates for the Eagle Ford shale (Hauwert, 2009).

Groundwater tracing, geochemical studies, geological mapping, and recharge studies have helped to refine our understanding of recharge sources to Barton Springs. Tracing has defined three groundwater basins, the Cold Springs groundwater basin and the Sunset Valley and Manchaca groundwater basins, both of which discharge at Barton Springs. Analogous to a highway system, the Edwards Aquifer has tributary groundwater flow conduits that converge onto larger flow trunk conduits (Figure 1). The major preferential groundwater flow paths can be distinguished by recovery of groundwater tracers injected far away, by potentiometric-surface troughs and mounds, by high transmissivity, and occasionally by high turbidity reflecting rapid groundwater velocity. Under normal to high spring flow conditions, groundwater velocities of 7 miles per day are common, diminishing to 1 mile/week or slower under drought conditions. Instead of taking 3 years for flow from Onion Creek to reach Barton Springs, tracers required only 3 days for intial arrival during high springflow conditions (3 weeks during low springflow conditions). The Manchaca groundwater basin is fed by two mapped preferential flow paths, the Manchaca flow route and Saline-Line flow route.

The Barton Springs outlets are fed by different mixtures of sources, as reflected in the varying chloride and sulfate concentrations (Hauwert et al., 2004). Upper Barton Springs may be fed entirely by the Sunset Valley groundwater basin, which is relatively urban. Old Mill Springs is fed primarily by the Saline-Line flow route which traces under thick overburden cover of the artesian zone parallel to IH35 south toward its main source of Onion Creek. By far most flow of the Barton Springs segment flows along the Manchaca flow route under confining units of the artesian area south to Onion Creek. Eliza Springs is most represented by the Manchaca flow route in quality. Main Barton Springs, discharging into Barton Springs pool primarily consists of flow from the Manchaca flow route, but is diluted slightly by contributions by both the Sunset Valley groundwater basin and Saline-Line flow route. It is the fact that most of Barton Springs flow is derived far south in largely rural area and that its flow isolated by confining layers from much local urbanism that the quality remains excellent as a treasured recreational pool.

There is still ongoing research to better understand the role of small pores and other mechanisms for long-term storage in the aquifer (Massei et al., 2007; Hauwert, 2011). One general hypothesis is that only 10% of the aquifer flow is transient, while the remainder is stored longer term (Slade et al., 1986). This might be visualized as a bathtub, where flow discharges at upper overflow drains when overfull. Another perhaps related hypothesis is that most water is stored in small pores in the matrix of the aquifer, and drain through relatively few conduits that integrate the aquifer (Worthington, 1999). Another hypothesis is that springflow is sustained by flow actively entering the aquifer system through conduits integrated throughout the aquifer, but temporary storage occurs as flow from major recharge sites and conduits "back up" into the adjacent aquifer in well-integrated extensive caves, fissures, and solution cavities (Hauwert, 2009; .Hauwert, 2011). One recent finding is that the Blanco River is a source for Barton Springs and plays an important role in sustaining its springflow during droughts (Hauwert et al., 2011). Likely all three hypotheses play some role in the aquifer system.

New recharge studies help refine source contributions to Barton Springs. An eddy covariance tower was used in a 46-acre sinkhole basin over a 1.4 year period (which experienced 21% above-average annual rainfall) in order to measure evapotranspiration. The study extrapolated that 29% of Barton Springs flow originated from upland intervening areas (Hauwert, 2009). A 2003 to 2007 stream flow loss water budget attributed 54% to 67% of Barton Springs flow and pumpage to major stream channel infiltration from Barton, Williamson, Slaughter, Bear, Little Bear, Onion, and Blanco River (Figure 3; Hauwert and Slade, 2011). The remaining 33 to 44% of Barton Springs flow and pumpage originated largely from intervening infiltration from the recharge areas between the major creeks, as well as lesser amounts from possible sources including Trinity Aquifer subsurface leakage, Saline Zone leakage, urban leakage, and flow from the San Antonio Segment of the Edwards Aquifer.

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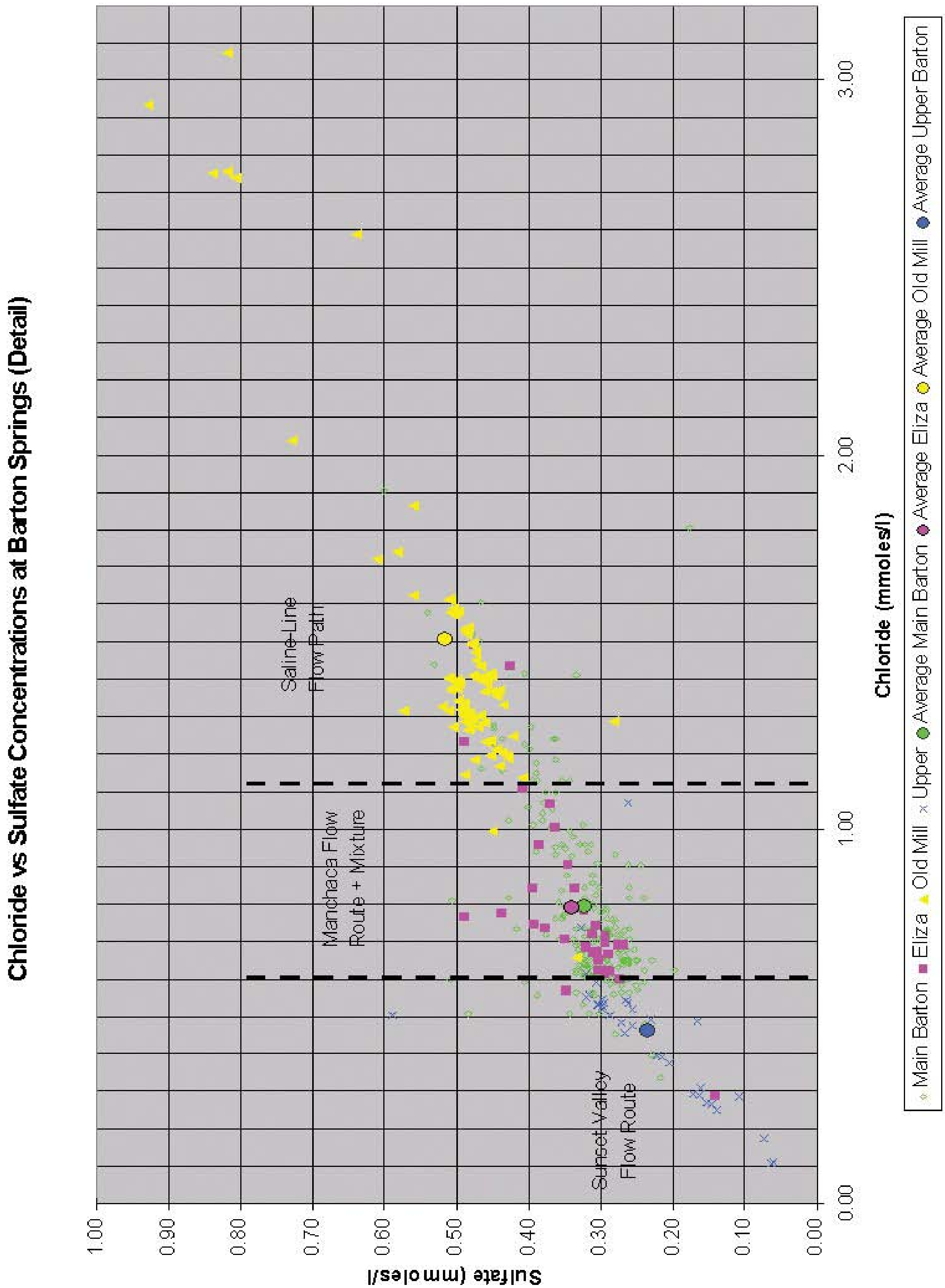
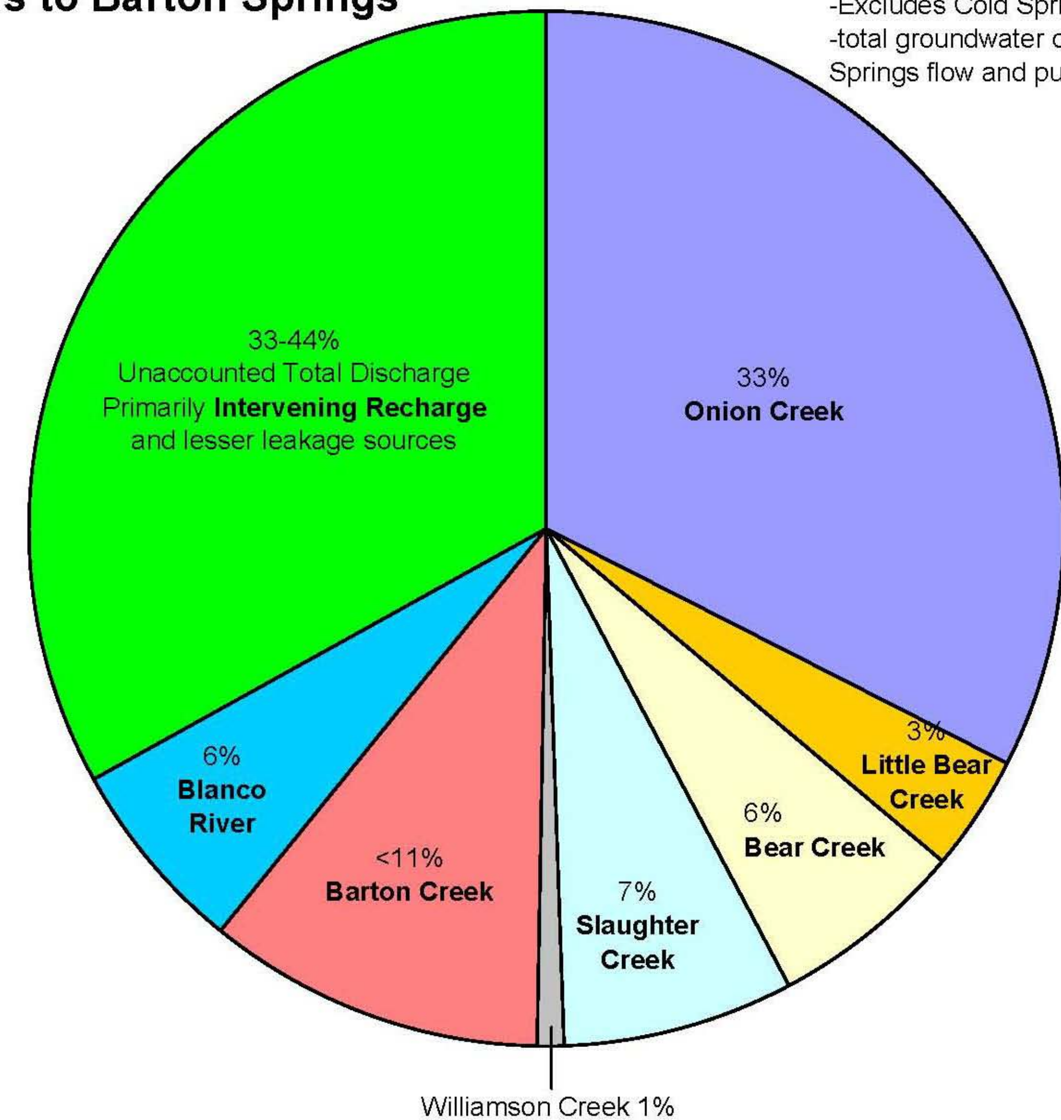


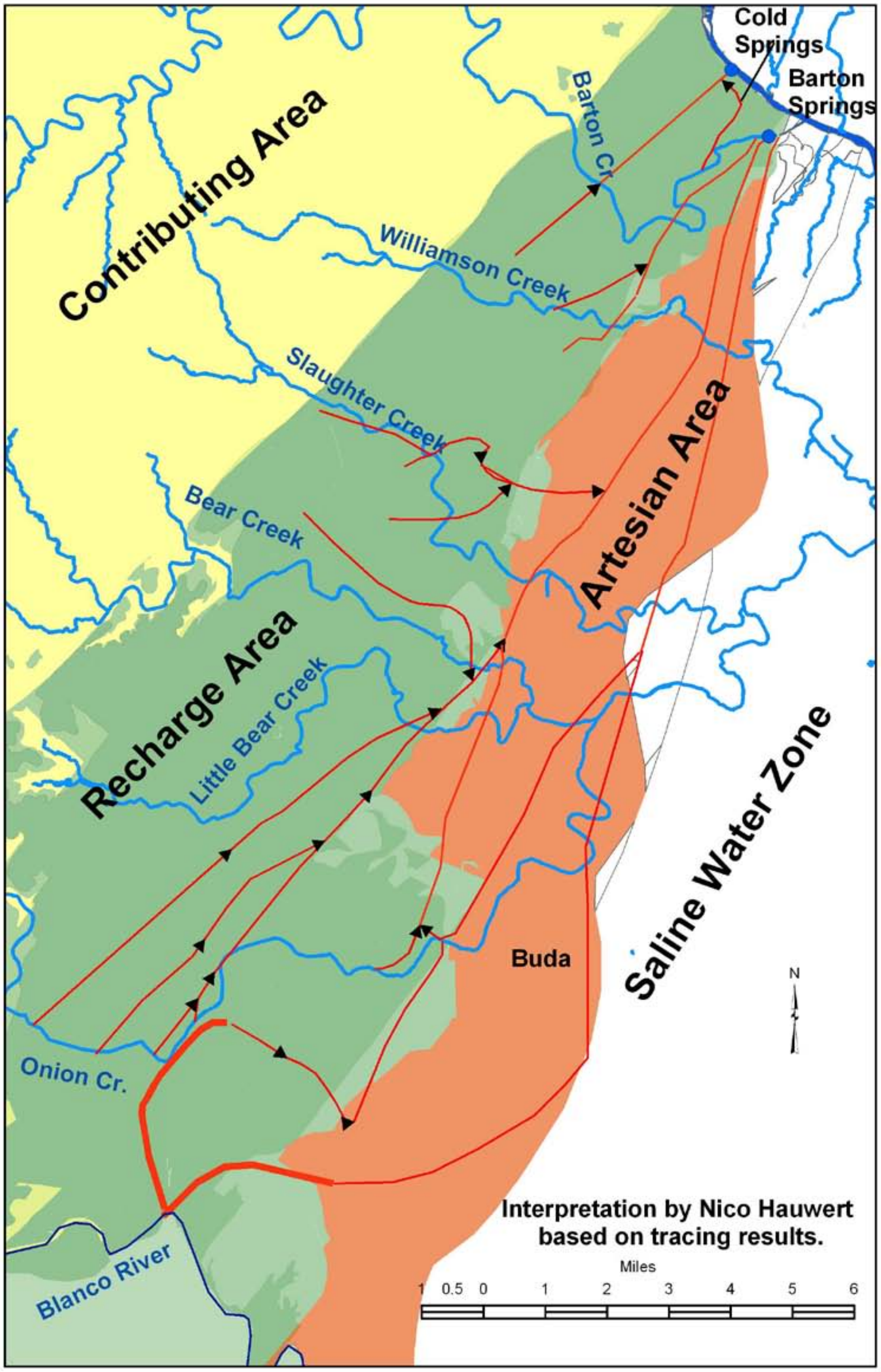
Chloride vs Sulfate Concentrations at Barton Springs (Detail)
Sulfate (mmoles/l)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Chloride (mmoles/l)
0.00
1.00
2.00
3.00
Saline-Line Flow Path
Manchaca Flow Route + Mixture
Sunset Valley Flow Route
Main Barton
Eliza
Old Mill
Upper
Average Main Barton
Average Eliza
Average Old Mill
Average Upper Barton

Recharge Contributions of Major Stream Channels to Barton Springs

-May 31, 2003 to September 19, 2007 Interval
-Excludes Cold Springs Groundwater Basin
-total groundwater discharge includes all Barton Springs flow and pumpage

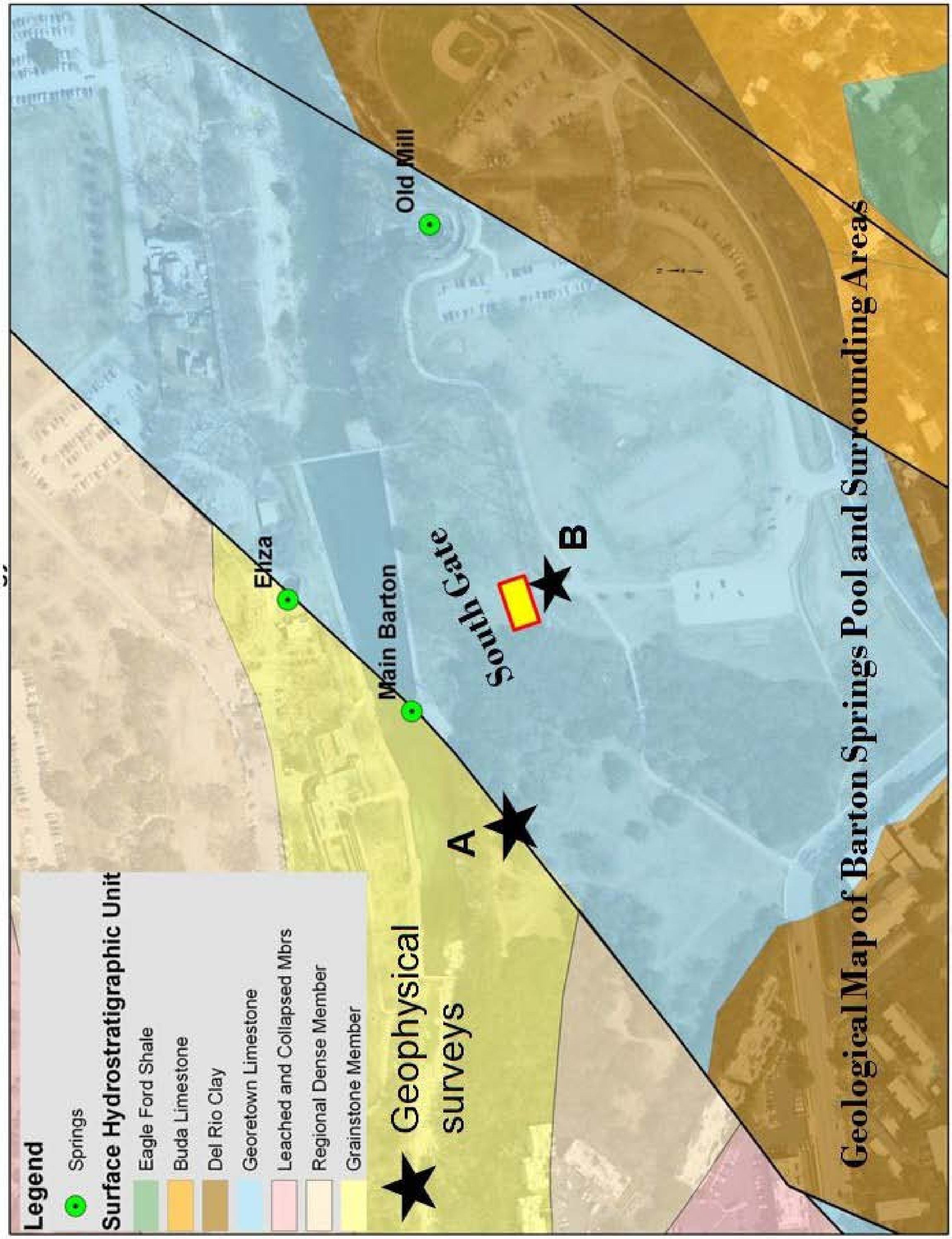


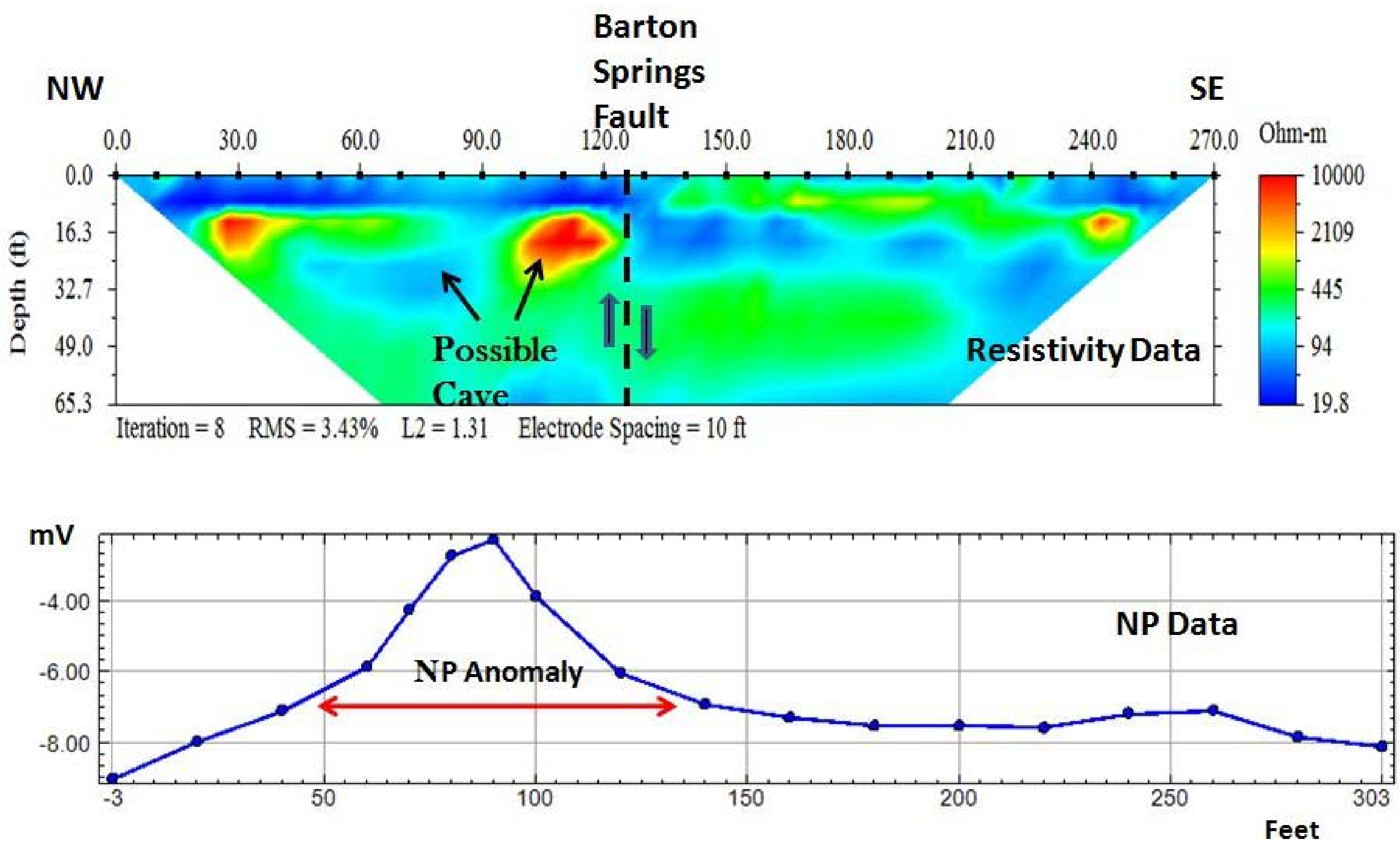
Groundwater Flow Paths



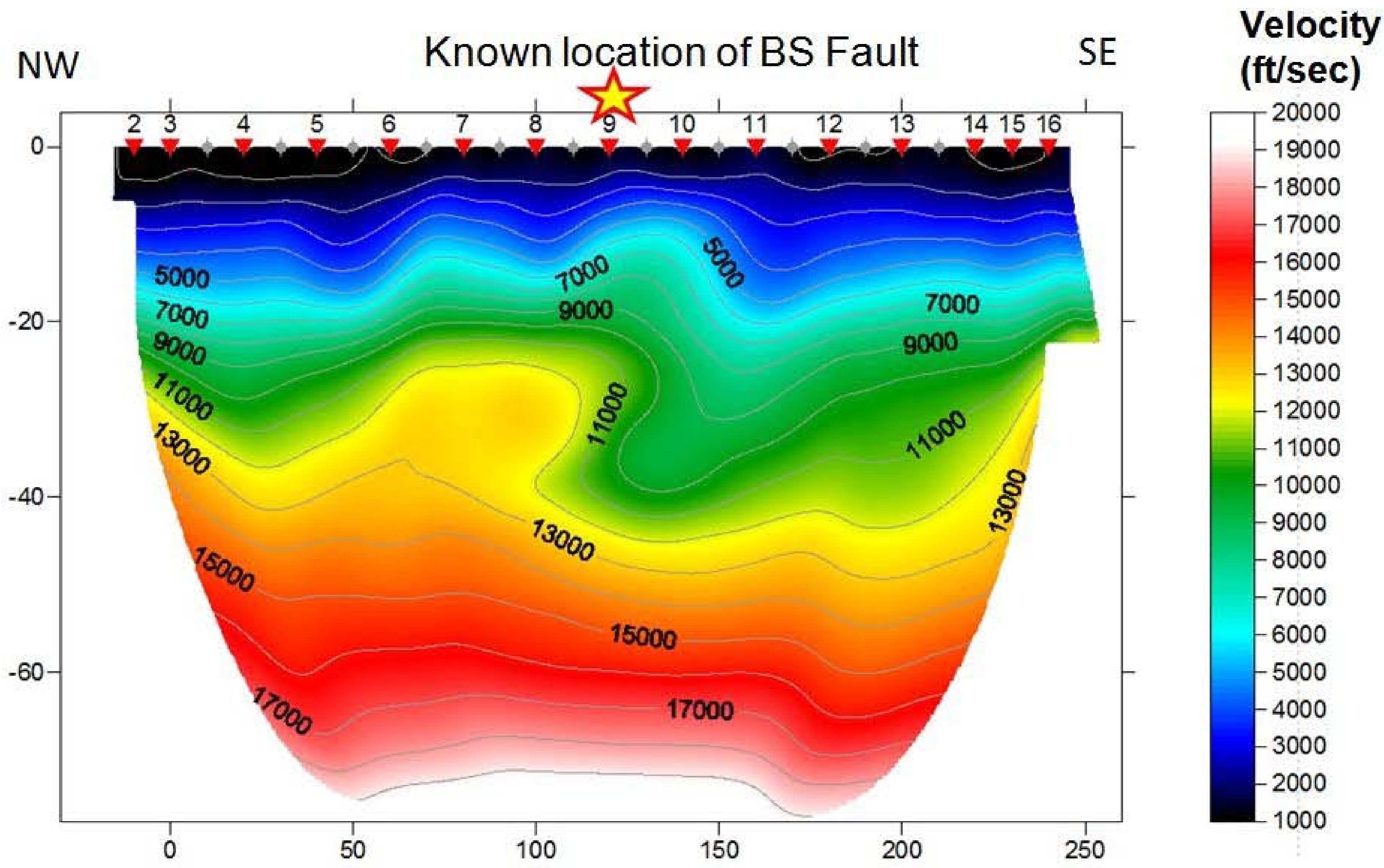
Stop 2: Barton Springs Geophysics

Mustafa Saribudak, Ph.D.
EGA, Houston Texas

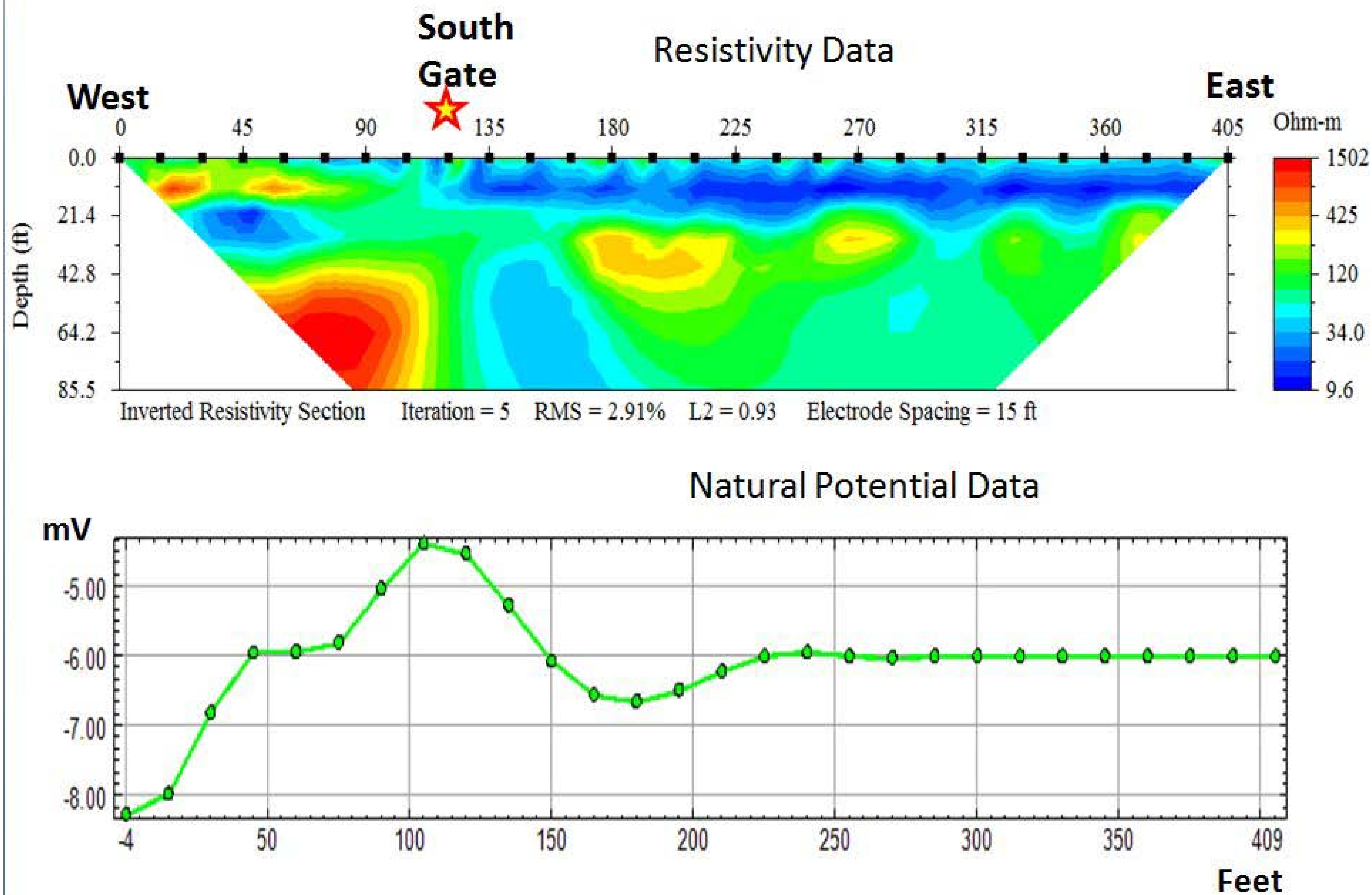




Resistivity and natural potential data across Barton Springs Fault at location **A.**

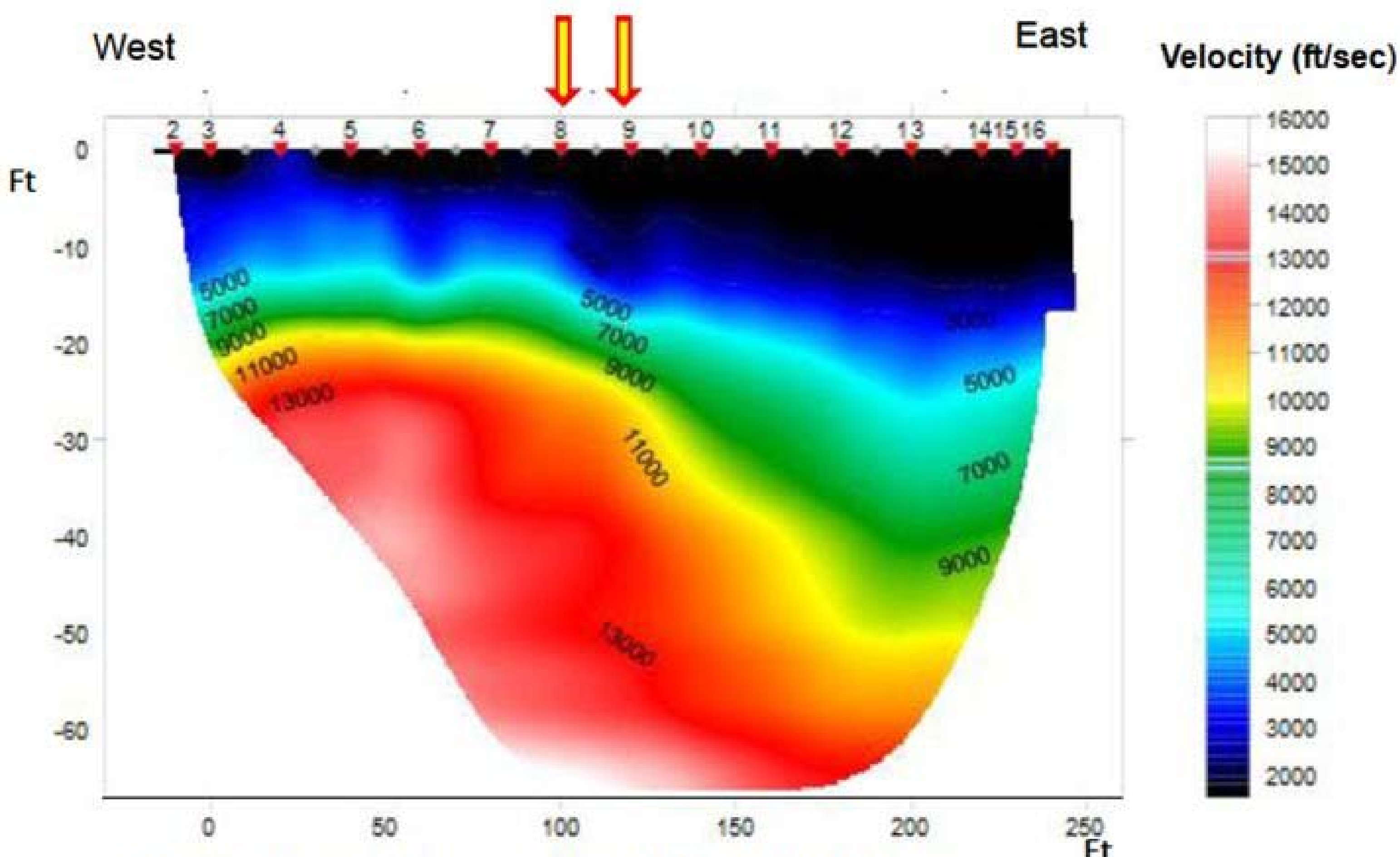


Seismic refraction tomography profile along the resistivity and NP profiles at location **A.**



Resistivity and natural potential data at location **B** in Zilker Park.

Seismic Refraction Tomography Data at Location **B** in Zilker Park



Seismic refraction tomography of **Line 1.** Note the low velocity zone to the immediate east of the pool gate.