A Look at the Hydrostratigraphic Members of the Edwards Aquifer in Travis and Hays Counties, Texas

Nico M. Hauwert and John A. Hanson, Coordinators

GUIDEBOOK

Austin Geological Society
P.O. Box 1302
Austin, Texas 78767

May 1995

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Bill Stein, Robert Botto, Donald Rauschuber, Charles Woodruff, Neven Kresic, Arthur Busbey, and Ken Morgan

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Cover

The cover shows Backdoor Springs and Cave, along Barton Creek on the Barton Creek Greenbelt. The porosity of this massive bed is due to dissolution of abundant caprinid fossils. This bed lies within the Dolomitic Member of the Edwards Group.

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INTRODUCTION

This guidebook represents an update on current research focusing on the Barton Springs segment of the Edwards aquifer. The accompanying field trip will focus on the field identification of the hydrostratigraphic units of the Edwards Group as described by Rose (1972) and Maclay and Small (1984). A portion of the current research activities are described in articles included in this book. Some of the ongoing research is summarized below.

The Barton Springs/Edwards Aquifer Conservation District (BS/EACD) is involved in a number of research studies of the Barton Springs Edwards aquifer. BS/EACD has recently completed a report of water-quality and hydrogeologic information that they have collected over the last four years. BS/EACD continues to monitor aquifer levels through ten water-level monitoring wells. BS/EACD is conducting a geological mapping project of the Barton Springs recharge zone with the United States Geological Survey (USGS) and funding from the Texas Water Development Board (TWDB). The BS/EACD continues to collect water-quality information, with the help of equipment purchase funding from the TWDB. The BS/EACD is reviewing required hydrogeologic studies for major pumping systems that utilize aquifer tests to assist in water-supply management of the aquifer resources. A summary of some of the water-supply usage from the Barton Springs Edwards aquifer is included in this book. An enhanced recharge study is being conducted by the BS/EACD with funding from the Environmental Protection Agency. The BS/EACD recently initiated a Regional Water Supply Study that will examine alternatives to groundwater usage and examine the limitations of the Barton Springs segment. A groundwater tracing study by BS/EACD is currently pending on grant funding sources.

The USGS has conducted detailed mapping of the hydrostratigraphic members of the Edwards aquifer recharge zone from West Texas east to Hays County with assistance from the Edwards Underground Water District. This mapping is continuing through Travis County with assistance from BS/EACD and funding from the TWDB.

The USGS has conducted water-quality sampling on a semi-annual basis from a number of wells and springs in the Barton Springs Edwards aquifer with funding from the City of Austin. As a part of this study, the USGS collects mutiple samples from two wells following rain events to measure temperature and chemical effects of recharge sources. In addition to the samples collected by the USGS, the City of Austin Environmental and Conservation Services Department (ECSD) is collecting water-quality samples from major springs and are analyzing them for a more comprehensive list of water-quality parameters. The ECSD is also utilizing two monitoring probes to continuously measure water quality changes in the major springs of the Barton Springs Edwards aquifer. ECSD is currently analyzing this data and will produce a report of their findings.

ECSD is currently studying the Barton Springs salamander, which is proposed for listing as an endangered species, to document and evaluate populations, population distributions, species extent, and habitat quality. The effort also includes establishing a captive breeding program.

The University of Texas Center for Research in Water Resources is completing a study to measure the water-quality characteristics of roadway runoff over the Barton Springs Edwards aquifer for the Texas Department of Transportation. The Center has also begun a study to construct a numerical model of the Barton Springs Edwards aquifer for the City of Austin. This model is designed as a management tool to assess the water quantity and water quality impacts from urban development.

Barbara Mahler of the Department of Geology at the University of Texas is performing a study of sediment source and transport within the Barton Springs Edwards aquifer.

L.B. Guyton and Associates has recently completed a study to gather information to help delineate the groundwater divide between the Barton Springs segment and the San Marcos segment of the Edwards aquifer. A summary of their findings is included in this book.

The Texas Speleological Association continues to perform mapping of caves in the Barton Springs segments, a slow and tedious but important step in the understanding of geological influences on subsurface water flow.

A discussion of geomorphological research by Texas Christian University is included in this guidebook.

ACKNOWLEDGEMENTS

The fieldtrip would not be possible without the support of the participating landowners including Al Wenzel, Joe Word, Joe Rodgers, and the City of Austin Parks and Recreation Department. I would like to acknowledge Eric Wendt, Brian McLaughlin, Dolores Bustillos-Tracy, and Bob Willett as well as all of the contributing writers for their assistance in putting together this book. Jim O' Connor and the Edwards Underground Water District performed geophysical logging of the Boorheim-Fields well and other some of the other wells discussed in this book. Ted Small of the U.S. Geological Survey provided valuable insight on the geology of the sites visited on the field trip. Jim Samson, the Austin Geological Society field trip coordinator, assisted in compiling the field trip road log and in the planning of the field trip. David Johns provided some review of the text. My finance Susan Wall gave her patience and support for the field trip.

SUGGESTED FURTHER READING

Guidebook to the Geology of Travis County, 1977, by Keith Young, published by the University of Texas Student Geological Society.

Carbonate Geology and Hydrology of the Edwards Aquifer in the San Antonio Area: 1984, Maclay, R.W. and Ted A. Small, U.S. Geological Survey. 72 pp.

Zilker Park Walking Tour Guidebook: A Recreational Visit to the Edwards Limestone: 1994, by Jennifer L. Walker and Paul R. Knox, Gulf Coast Association of Geological Societies 1994 Convention. 48 pp.

Edwards Group, Surface and Subsurface, Central Texas: 1972, by Peter R. Rose, Bureau of Economic Geology Report of Investigations No. 74.

AGS 1995 Field Trip
ROAD LOG

Mileage

Barton Springs/Edwards Aquifer Conservation District Office
8:00 P.M.
Edwards Aquifer Research and Data Center, Freeman Building
8:30 P.M.
San Marcos Loop 82
Turn right onto Post Road
Turn left on Lime Kiln Road

Lime-Kiln Quarry 9:00-10:30 P.M.

This quarry exposes the contact between the Georgetown Formation and the underlying Marine Member of the Edwards Group. The Georgetown Formation is distintively nodular and contains an abundance of fossils including gryphea, kingena, pectins, arctostrea, and ammonites. The underlying surface at the top of the Marine Member is an oxidized, reddish horizon that contains borings and toucasia fossils. The Marine Member exposure contains an abundance of caprinids, toucasia, and burrows.

A fault can be seen crossing midway through the quarry. In the northwestern side of the quarry, the entire section of the Georgetown can be observed overlain by the Del Rio clay. A cave has developed near the top of the Marine Member in western wall of the quarry. This horizontal cave demostrates both the tendency for cave development in the Marine Member and structural control imposed by fractures that parallel the nearby fault.

0.00 Zero your mileage counter. Turn left on Lime Kiln Road.
1.4 Turn right onto Post Road
1.8 Turn left onto Loop 82
3.1 Enter ramp onto Interstate 35 going north
12.9 Exit Interstate 35 and turn left onto Loop 4. Follow the Loop 4 signs into the City of Buda.

The Buda area is heavily reliant on groundwater from the Barton Springs Edwards aquifer. Aquifer tests that are being performed on the major pumping systems help in the management of the water *resources, and contribute a wealth of information on the hydrogeology of this area. An article by Robert Botto in this guidebook describes the distribution of groundwater usage in the Barton Springs Segment.*

15.8 Cross Railroad Tracks
16.2 Turn Left onto Ranch Road 967
19.1 Turn right on FM 1626
19.9 Turn left onto Jerry's Lane
20.6 Turn left onto Elliot Ranch Road
21.0 Turn left at four-way stop
22.0 Turn right at gate to Borheim-Fields Quarry

Boorheim-Fields Quarry 11:00-12:15 P.M.

An abandoned quarry in north Hays County. This quarry exposes the Leached-Collapsed and Regional Dense Members. A measured section of the quarry exposure and a gamma log survey of a nearby water well on the quarry site (state well no. 58-49-926) is included in this book. The Leached and Collapsed section includes the wall exposures in the main pit. It consists primarily of wackestone with calcite geodes. Two chert horizons are visible. Fossils of toucasia, pectin, and caprinids can be found here in the Leached and Collapsed Members. Note the cave located just north of the quarry pit, positioned in the Collapsed Member. The floor of the main pit roughly follows the contact with the underlying Regional Dense Member (RDM). This contact can be seen as an increase in natural radiation on the gamma log. Ripples, dessication cracks, weathered horizons and other signs of aerial exposure during deposition are visible here. Please stay out of the lower, water-filled pit as it has a very treacherous slope and is reported to contain water moccasins. We will have the opportunity to observe the RDM upclose in an upcoming stop.

25.1 Turn left onto road from Boorheim-Fields Quarry gate.
26.2 Turn right onto Elliot Ranch Road at four-way stop.
26.6 Turn right onto Jerry's Lane
27.3 Turn right onto FM 1626.
28.1 Turn right at the intersection of FM1626 and Ranch Road 967.
35.1 Turn left into Joe Rodgers Quarry

Joe Rodgers Quarry 12:30-1:30 P.M.

This quarry exposes the lower Dolomitic Member of the Edwards Group. Note the abundant, characteristic burrows and abundant caprinid fossils.

35.4 Turn left onto FM 967
37.2 Turn right onto FM 1826
43.7 Turn right onto Outer Loop
48.9 Intersection of Slaughter Lane and Mopac

Crossing three petroleum pipelines: Shell Rancho pipeline (crude oil), Phillips EZ pipeline (liquid natural gas), and Exxon (crude oil) pipeline.

Three major petroleum pipelines cross the Barton Springs Edwards aquifer here, carrying petroleum from west Texas to the coast. Major crude oil spills occurred in this vicinity in both the Rancho pipeline and the Exxon 18-inch pipeline. The amount of oil recovered from the spill ranged between 980 barrels to 2,100 barrels. In each case the pipeline was ruptured by contractors performing roadway and utility construction. For this reason, it is important for environmental professional performing environmental assessments for proposed construction sites near petroleum pipelines to inform contractors of the significant of the pipelines. When performing excavation near the pipelines, the pipeline companies should be notified well in advance of construction at the phone number posted on the yellow pipeline warning signs.

Since the Rancho pipeline rupture in 1986, Shell Pipeline has met with local agencies to coordinate future response to a possible spill, prepared a spill response vehicle, and incorporated local agencies in "table-top" exercises to simulate the response to a spill. Some accounts of these spills can be found in "Pipeline oil spills and the Edwards Aquifers. Central Texas, by Pete Rose in The Balcones Escarpment, Central Texas, printed by the Geological Society of America in 1986, and "Edwards Stratigraphy and Oil Spills in the Austin, Texas Area", by William Russell in the April 1987 Texas Caver magazine. James Quinlan offers some steps to prepare for accidental spills over a karst aquifer in "Recommended procedure for Evaluating the Effects of Spills of Hazardous Materials on Ground Water Quality in Karst Terranes" published by the National Groundwater Association in the Proceedings of the Environmental Problems in Karst Terranes and Their Solutions Conference, 1986.

51.9 Intersection of Highway 290 and Mopac.
53.2 Crossing Barton Creek
53.8 Exit Mopac and turn left onto Loop 360.
56.5 Turn left at Stoneridge Road across Loop 360 onto dirt road.

Barton Creek Greenbelt 2:00 P.M.

Enter the gate and turn right (do not go straight down hill). As you approach the Electric Substation, park near dirt road to the left. Walk along the dirt road heading south for about 1,000 feet.

Cave Y 2:15 P.M.

This cave is formed in the lower Grainstone and upper Kirschberg Members. Note the well developed sinkhole.

Continue downhill on dirt road. *The abundant remnant chert fragments, terra rosa, and heavily recrystallized rock exposures of Kirschberg Member. The contact with the underlying Dolomitic Member is not well defined here, due to lack of exposure or faulting. Following the break in slope you may observe toucasia-rich bed of the Dolomitic Member.*

At the intersecting path near Barton Creek, take a right and follow the path for a few minutes to Sculpture Falls. We will regroup here and enjoy the scenery. *The massive bed of the Dolomitic Member that the falls spill over is honeycombed due to the dissolution of caprind fossils.*

2:45 pm Walk back on path downstream along Barton Creek. You may observe some old stonewalls on the left hand side about 0.3 miles downstream. Turn left into the first creekbed, immediately following the stonewalls. Follow creekbed upstream.
A short distance up the creek we can see a fault that exposes the Regional Dense Member on the upstream side. Pleuromya knowltoni fossils are the pistachio-shaped clam fossils that are abundant in the RDM exposures here.

Backdoor Cave and Springs 4:00 P.M.

These springs constantly flow at a rate of about 10 gallons per minute, except during periods of extended drought which indicates a diffuse flow source. Water-level measurements from nearby wells *in March 1993 suggests that the spring is perched well above the saturated zone (Barton Springs/Edwards Aquifer Hydrogeology and Groundwater Quality, 1994, by the Barton Springs/ Edwards Aquifer Conservation District). Caprinids are visible in the roof of the cave entrance. Dissolution of the caprinids creates a honeycombed texture and thereby contributes to the high permeability of this strata.*

Follow the creekbed just downstream of Backdoor Spring, informally called "Split Canyon."

"Split Canyon" 4:30 P.M.

This canyon provides probably the best exposure of the Dolomitic Member within the Barton Springs Segment. As you ascend the creek watch for the argillaceous rythmic marker bed at the canyon split, and the Dictyoconus walnutensis marker bed further upstream.

Head Back to vans 5:15 P.M.

Take Right onto Loop 360.
Take Right onto Mopac (Loop1) and go south.
Take left onto Slaughter Lane and go east.
Take right onto Manchaca Road and go south two miles.
Take left on Regal Row before Texaco Station. Turn left into District office and drop off Austin attendants (6:00 pm).
Continue to Freeman Building in San Marcos (6:30).

HYDROGEOLOGY OF THE EDWARDS AQUIFER LIMESTONE IN HAYS AND TRAVIS COUNTIES

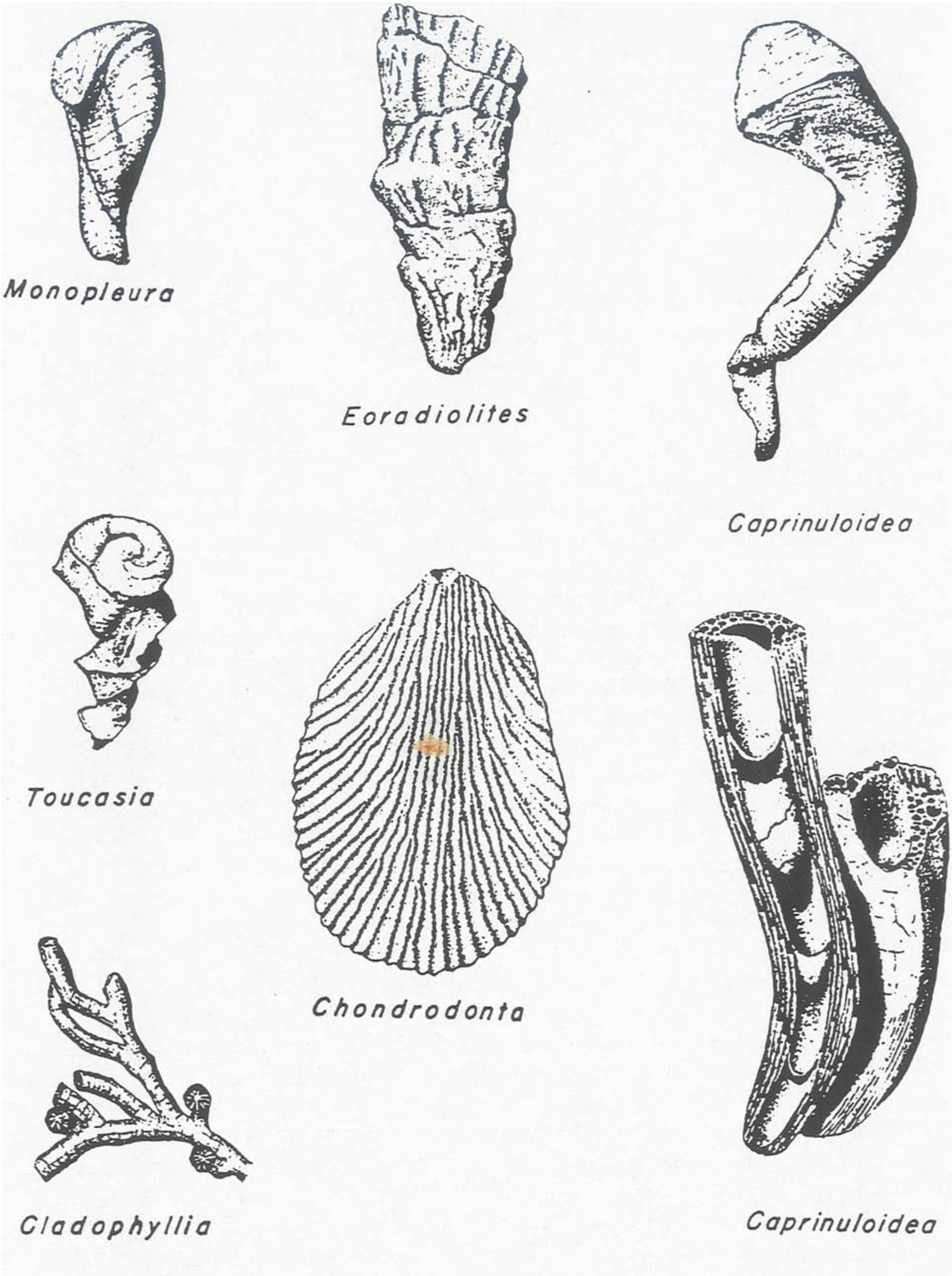
by

John A. Hanson

Introduction

Personal research and the work of others have shown that at the time of deposition of this part of the Lower Cretaceous sequence, the Llano Uplift and the surrounding Central Texas Platform formed a high area. Plunging southeastward from this high area was the San Marcos Arch. The Angelina-Caldwell Flexure crossed the San Marcos Arch between the present positions of San Antonio and the Texas coast and parallel to the latter. At the beginning of Rodessa-Upper Glen Rose deposition the rudistids (a collective term used to include pelecypods of the Rudistaceae, Chamaceae, Pernidae, and Mytilacea, Figure 1) and associated organisms became established along this flexure and began to construct the barrier reef which ultimately became one of the major reef trends in the geologic column. Behind this reef trend the North Texas Basin extended without obvious interruption from the Central Texas Platform into Louisiana and north to the mountains of Oklahoma. The pattern of deposition noted above remained fairly stable until the end of Trinity or the beginning of Fredericksburg deposition. At this time, the reef-building organisms began to transgress landward along two main paths: (1) northwestward around the flank of the Llano Uplift and across the shallow shelf in north central Texas and (2) northward over the rising Sabine Uplift as far north as southwestern Arkansas and southeastern Oklahoma. By the end of Fredericksburg deposition, the extension of the reef complex in north central Texas had effectively subdivided the former North Texas Basin into two very different environments of deposition behind the main barrier reef trend: an open marine shelf which is herein referred to as the Tyler Basin and a shallow restricted basin, the Kirschberg Lagoon over the Central Texas Platform. Fredericksburg deposition in north central Texas was brought to a close by slight emergence and the development of a minor unconformity (Nelson, 1973).

Regional differences in the porosity and permeability of the Edwards aquifer are related to three major depositional areas, the Maverick basin, the Devils River trend, and the San Marcos platform, that existed during Early Cretaceous time. The rocks of the Maverick basin are predominantly deep basinal deposits of dense, homogeneous mudstones of low primary porosity. Permeability is principally associated with cavernous voids in the upper part of the Salmon Peak Formation of local usage in the Maverick basin. The rocks of the Devils River trend are a complex of marine and supratidal deposits in the lower part and reefal or inter-reefal deposits in the upper part. Permeable zones, which occur in the upper part of the trend, are associated with collapse breccias and rudist reefs. The rocks of the San Marcos platform predominantly are micrites that locally contain collapse breccias, honeycombed, burrowed mudstones, and



From Young, 1977

Figure 1

rudist reef deposits that are well leached and very permeable. The rocks of the San Marcos platform form the most transmissive part of the Edwards aquifer in the San Antonio area. Karstification of the rocks on the San Marcos platform during the Cretaceous time enhanced the permeability of the aquifer (Maclay and Small, 1984).

Permeability of the Edwards aquifer is greatest in particular strata (lithofacies) which have been leached in the freshwater zone. Groundwater moves along vertical or steeply inclined fractures that are passageways by which water can enter permeable strata. Water moves from the fractures into beds formed by collapse breccias, burrowed wackestones, and rudist grainstones that have significant secondary porosity and permeability. Water has selectively dissolved sedimentary features within those rocks to increase the size of the openings and the degree of interconnection between pore voids (Maclay and Small, 1984).

Stratigraphy of Hydrogeologic Members (Rose, 1972)

Marine member - Reefal limestone and carbonates deposited under normal open marine conditions. Zones with significant porosity and permeability are laterally extensive. Karstified unit. Limestone and dolomite; honeycombed limestone interbedded with chalky, porous limestone and massive, recrystallized limestone.

Leached and Collapsed member - Tidal and supratidal deposits, conforming porous beds of collapse breccias and burrowed biomicrites. Zones of honeycombed porosity are laterally extensive. Limestone and dolomite. Recrystallized limestone occurs predominantly in the freshwater zone of the Edwards aquifer. Dolomite occurs in the saline zone.

Regional Dense member - Deep water limestone. Negligible permeability and porosity. Laterally extensive bed that is a barrier vertical flow in the Edwards aquifer. Dense argillaceous limestone.

Grainstone member - Shallow water, lagoonal sediments deposited in a moderately high energy environment. A cavernous, honeycombed layer commonly occurs near the middle. Interparticle porosity is locally significant.

Dolomitic and Kirschberg members - Supratidal deposits toward top. Mostly tidal to subtidal deposits below. Very porous and permeable zones formed by boxwork porosity in breccias or by burrowed zones.

Basal Nodular member - Subtidal deposits. Negligible porosity and permeability. Limestone, hard, dense, clayey; nodular, mottled, styolitic.

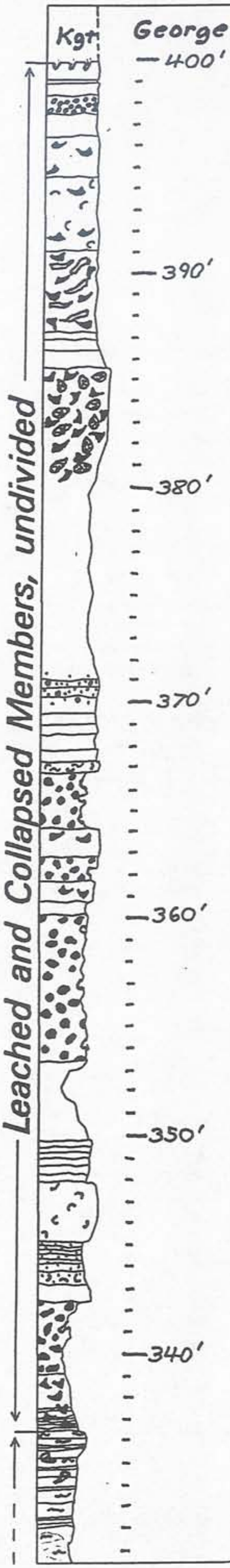
Discussion

While working at the U.S. Geological Survey, I had the opportunity to field map the hydrogeology of the Edwards aquifer recharge zone in Uvalde (in which Alan Clark had a part in), Comal (along with some mapping done by Bill Stein), Hays, and Travis counties. The purpose was to describe the hydrogeologic characteristics (porosity and permeability) of the limestones pertinent to movement and contamination of groundwater.

The Edwards aquifer recharge zone in Hays and Travis counties is of major concern to the city of Austin. Urban development has encroached upon the recharge zone creating the potential for surface runoff and consequent contamination infiltrating into the aquifer. The Edwards aquifer is now being characterized by its permeability/porosity within different subdivisions within the limestones. Hydrogeologic mapping that has been completed will help delineate the recharge patterns and the susceptibility of contamination in this area.

Faults were identified in the field by stratigraphic displacement and characteristics related to faulting , such as zones of fault gouge composed of soils that resemble caliche, or relatively thick vein-like masses of euhedral to subhedral calcite. The strata at some localities were steeply inclined as the result of drag-folding or a product of structural failure related to faulting. Most faults trended north twenty degrees east to north thirty-five east. Stream diversion, as an result of faulting, can also be seen geomorphically on maps in which meandering would evolve parallel at fault junctions.

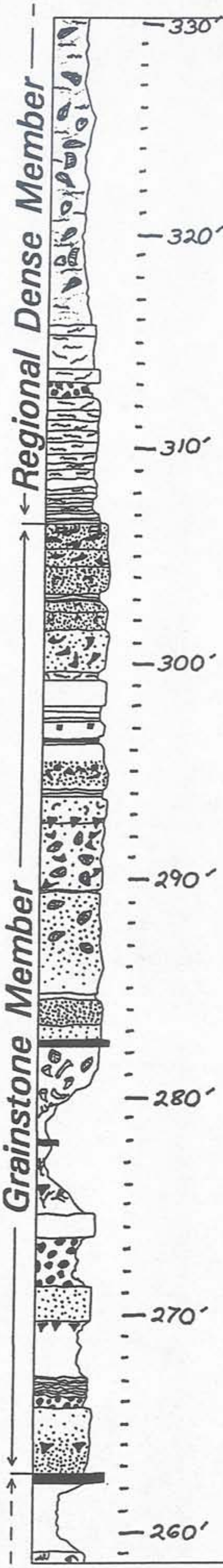
Minor changes in lithologies warranted a stratigraphic section to be done in Travis County (Figure 2). Various members were able to be laterally traced across the area whereas others had to be further defined. Thickness of the individual members in Travis County, for the most part, remained the same with the exception of the Marine member not being present as compared to the apex of the San Macros platform. Stratigraphic sections were described lithologically by Dunham (1962) classification, and porosity types by Choquette and Pray (1970) (Figures 3 and 4 respectively).



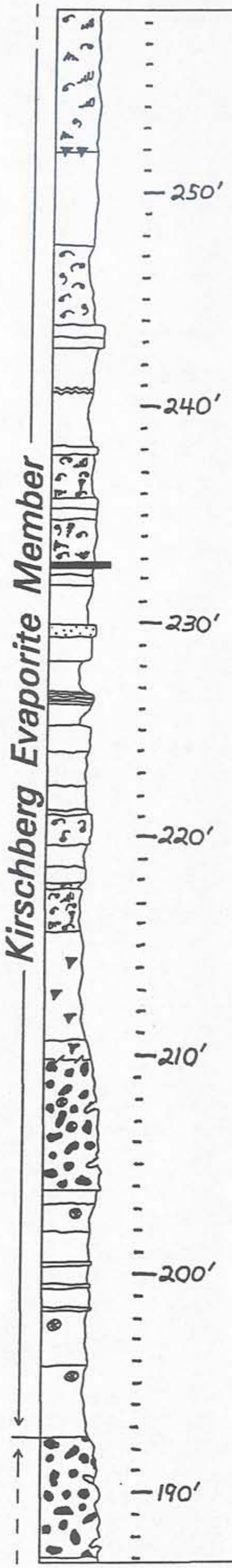
Georgetown Formation

400'	Bored and FeO_2 oxidized unconformable surface.
397.5-398.4'	Light tan allochem grainstone.
394.5-396.4'	Light tan burrowed micrite with some *Toucasia*.
391.0-394.5'	Light tan micrite with some *Toucasia* and spar filled shell fragments.
387.2-391.0'	Light tan-gray micrite; *Caprinid* and *Toucasia* wackestone.
379.5-385.3'	Light tan-gray micrite; *Chondrodonta* and *Toucasia* packstone (biostrome).
	Note: *Montastrea sp.* coralline masses have been found approx. 20-40' above the contact of the Regional Dense Member.
371.0-379.5'	Light tan-gray punky micrite; mudstone; intercrystalline pinpoint porosity.
369.8-371.0'	Light tan micrite; allochem and *miliolid* wackestone.
367.3-369.8'	Light tan micrite; mudstone.
366.9-367.3'	Light tan micrite with a few spar filled shell fragments and FeO_2 wispies.
364.1-366.9'	Tan-brown micrite; good vuggy porosity.
362.9-364.1'	Tan micrite with some *Toucasia* shell fragments.
361.8-362.9'	Tan micrite; good vuggy porosity.
360.8-361.8'	Tan micrite with some *Toucasia* shell fragments.
353.4-360.8'	Tan-brown micrite; excellent vuggy porosity.
349.9-353.4'	Light tan-gry punky to pulverulitic micrite; intercrystalline pinpoint porosity.
347.9-349.9'	Light tan micrite; mudstone.
345.2-347.9'	Light tan micrite with a few spar filled shell fragments.
343.9-345.2'	Light tan micrite with some *miliolids*
343.2-343.9'	Light tan micrite with some *miliolids* and spar filled shell fragments.
342.5-343.2'	Light tan micrite; mudstone.
339.1-342.5'	Light tan-gray punky micrite; dissolutioned burrow porosity good.
336.4-339.1'	Light tan-gray micrite; *Toucasia* wackestone.
333.9-336.4'	Tan argillaceous micrite with FeO_2 wispies and in some places a few *Monopleura*.

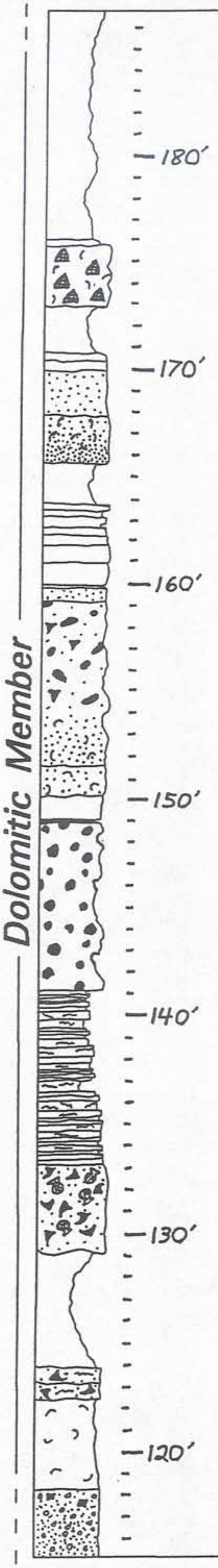
Figure 2



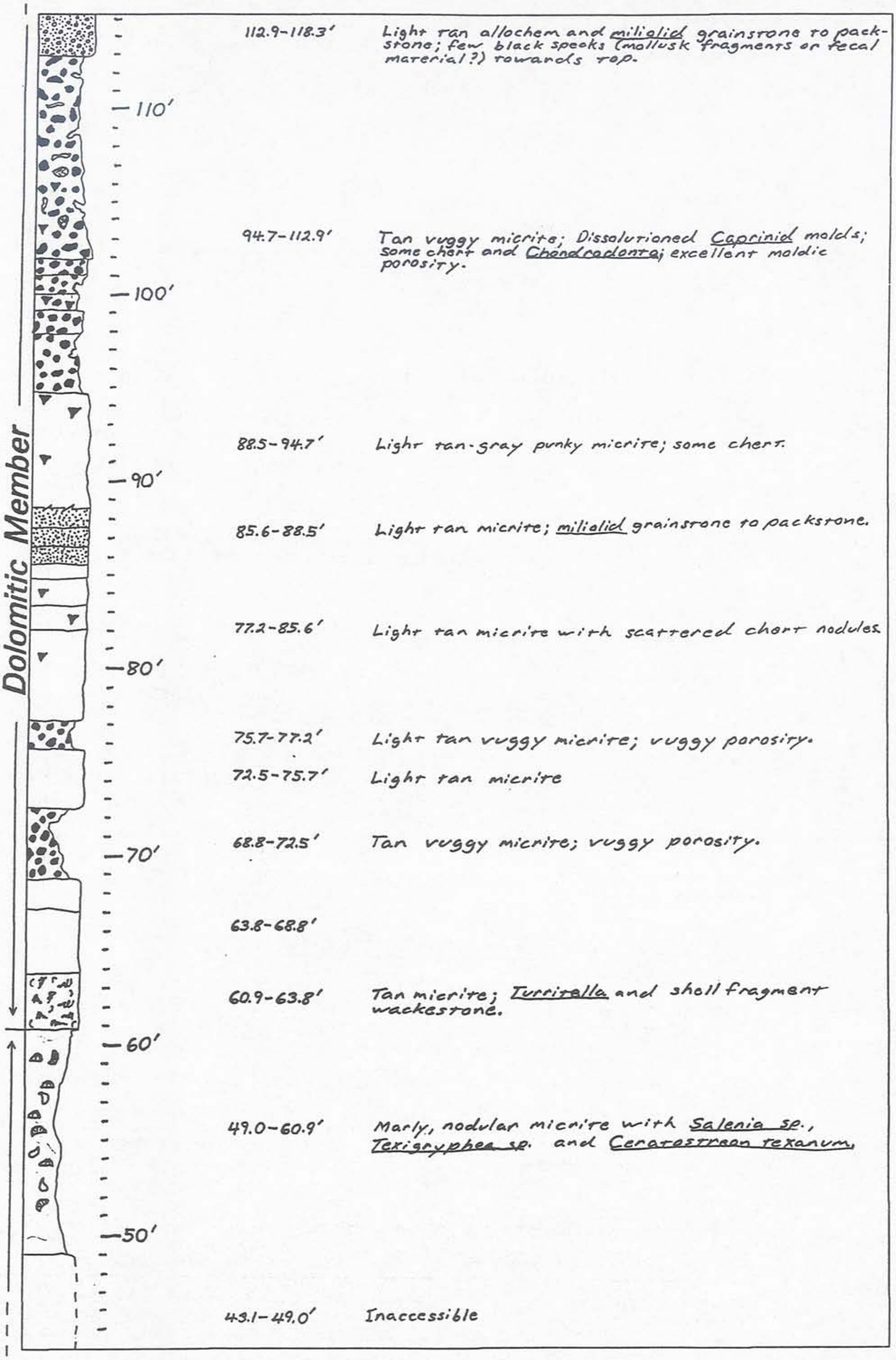
315.8-333.9'	Tan to tan-gray, nodular, argillaceous micrite with FeO_2 wispies and indigenous Pleuromya knowltoni (an index fossil for the Regional Dense Member), Protocardia sp., Exogyra sp. wackestone.
313.2-315.8'	Light tan-gray micrite with FeO_2 wispies; mudstone.
312.4-313.2'	Light brown micrite; vuggy porosity with Terra rosa infills.
311.3-312.4'	Light tan-gray micrite with some FeO_2 wispies; mudstone.
309.3-311.3	Light tan-gray porcelaneous micrite with FeO_2 wispies; mudstone.
306.7-309.3'	Light tan fissile micrite with some FeO_2 wispies; mudstone.
305.4-306.7'	Light tan miliolid grainstone with spar replaced stubby Turritella and rounded to subrounded clasts that resemble the lithology of the Regional Dense member.
304.5-305.4'	Light tan miliolid grainstone with spar replaced Toucasia.
301.6-304.5'	Light tan miliolid packstone with few spar replaced shell fragments.
299.8-301.6'	Light tan micrite; Toucasia and miliolid wackestone.
299.2-299.8'	Light tan-gray micrite with FeO_2 wispies (resembles the Regional Dense Member).
297.4-299.2'	Light tan micrite; mudstone, mottled.
296.6-297.4'	Light tan micrite with a few black specks (mollusk shell fragments or fecal material?).
296.2-296.6'	Light tan fissile micrite.
294.2-296.2'	Light tan micrite; spar replaced Turritella, shell fragment miliolid grainstone with some black specks (mollusk shell fragments or fecal material?), upper and lower bedding is abrupt (storm surge?).
293.9-294.2'	Light tan thin bedded micrite.
292.7-293.9'	Light tan micrite with a few miliolids and spar replaced pelecypod fragments; blue-gray chert nodules @ 292.7'.
289.5-292.7'	Light tan-gray micrite; Chondrodonta and Toucasia wackestone with some scattered miliolids.
284.9-289.5'	Light tan-gray micrite; Chondrodonta shell fragment and miliolid wackestone.
284.6-284.9'	Light tan micrite with some FeO_2 staining.
283.3-284.6'	Light tan micrite; miliolid packstone.
282.7-283.3'	Light tan-gray micrite with some miliolids.
282.4-282.7'	Blue-gray chert bed.
274.7-282.4'	Tan-white recessive pulverulite; Chondrodonta, Caprinid, Cladophyllia, and Monopleura wackestone (biostrome); Blue-gray, 3-4" chert bed @ 277.8', Blue-gray chert nodules @ 275.5'; intercrystalline to cavernous porosity.
273.6-274.7'	Light tan-gray micrite; mudstone.
271.3-273.6'	Light tan punky micrite; good vuggy porosity.
269.8-271.3'	Tan-brown micrite; miliolid wackestone.
267.1-269.8'	Light tan-gray punky micrite; Light gray chert nodules @ 269.8'; collapse breccia porosity.
266.2-267.1'	Tan-gray crinkly bedded micrite (algal?).
265.8-266.2'	Tan-gray punky micrite; vuggy porosity.
262.7-265.8'	Tan micrite; miliolid wackestone to grainstone; blue-black chert nodules @ 264.0'.
262.2-262.7'	Black to blue-gray chert bed.
259.0-262.2'	Tan-white recessive pulverulite; intercrystalline to cavernous porosity.

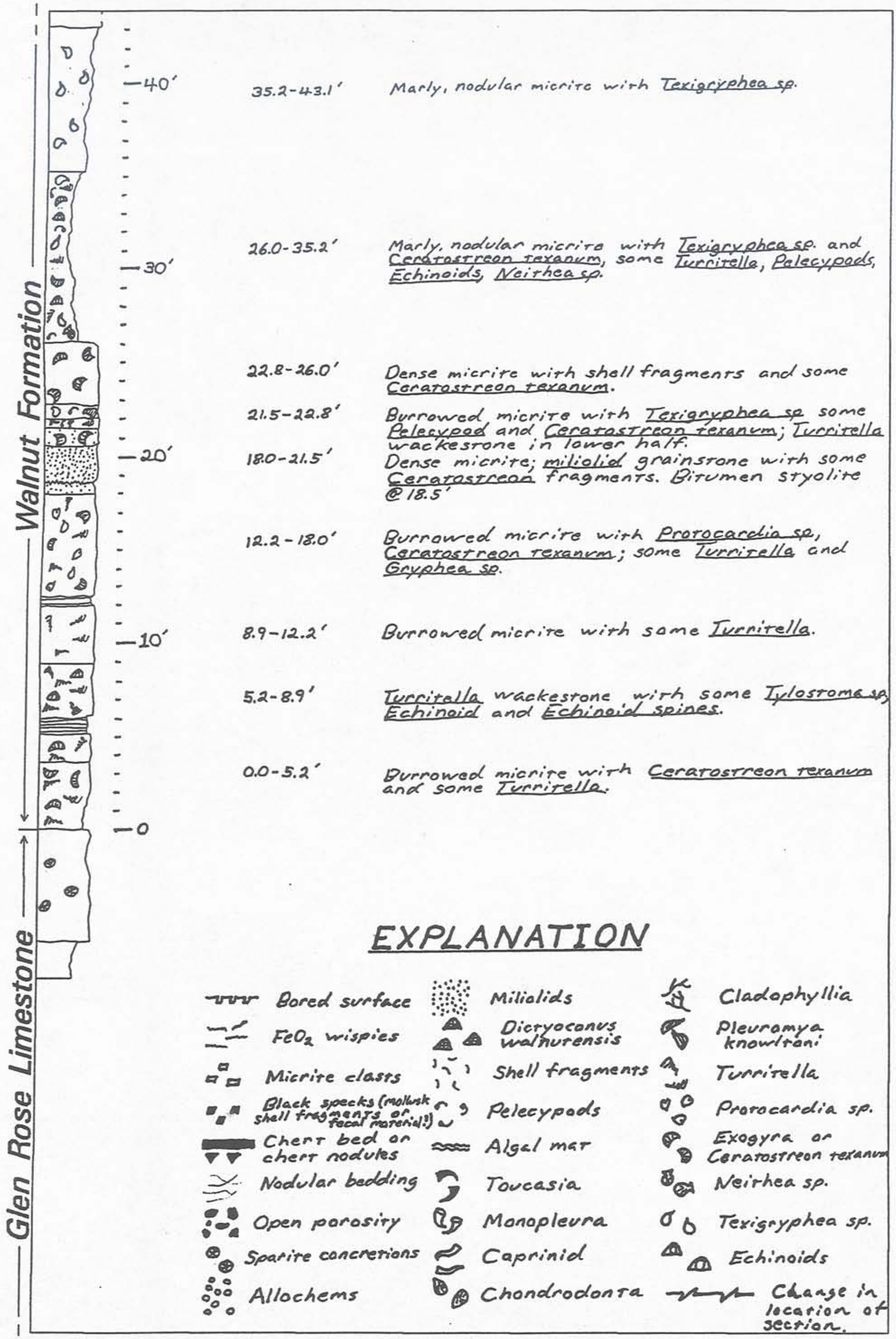


251.9-259.0'	Tan-white punky, dedolomitized micrite with some small _Turritella_ and _Pelecypod_ molds; pinpoint to moldic porosity.
247.6-251.9'	Light tan punky micrite; intercrystalline porosity; blue-brown chert nodules @ 251.9'.
243.8-247.6'	Light tan dedolomitized micrite with many _Pelecypod_ molds; pinpoint to moldic porosity.
242.7-243.8'	Light tan micrite; mudstone.
238.1-242.7'	Tan-white punky micrite; 2" algal mat @ 240.9'; intercrystalline porosity.
235.8-238.1'	Light tan dedolomitized micrite with _Pelecypod_ and _Turritella_ molds; pinpoint to moldic porosity.
234.8-235.8'	Light tan micrite; mudstone.
232.9-234.8'	Light tan dedolomitized micrite with _Pelecypod_ and _Turritella_ molds; pinpoint to moldic porosity.
232.5-232.9'	Brown chert bed.
229.9-232.5'	Light tan punky micrite; mudstone.
229.3-229.9'	Tan micrite; _miliolid_ wackestone.
228.2-229.3'	Light tan-gray micrite with some FeO_2 staining.
226.8-228.2'	Light tan punky micrite with some FeO_2 staining.
226.1-226.8'	Light tan micrite; rythmic bedded.
225.2-226.1'	Light tan dedolomitized micrite with some FeO_2 staining pinpoint to fenestral porosity.
221.1-225.2'	Light tan pulverulite; intercrystalline porosity.
219.7-221.1'	Light tan-gray punky micrite with some _pelecypod_ molds; intercrystalline to moldic porosity.
218.7-219.7'	Light tan-gray pulverulite; intercrystalline porosity.
217.9-218.7'	Light tan punky micrite with some FeO_2 staining.
217.6-217.9'	Light tan-gray pulverulite with _Pelecypod_ molds; intercrystalline to moldic porosity.
215.7-217.6'	Light tan punky dedolomitized micrite with some _Turritella_ and _Pelecypod_ molds; intercrystalline to moldic porosity.
209.9-215.7'	Tan punky dedolomitized micrite with scattered brown to blue-gray chert nodules.
203.8-209.9'	Tan very porous micrite with some euhedral to subhedral sparite concretions; dissolutioned burrow porosity.
192.6-203.8'	Tan punky to pulverulite micrite with some sparite concretions; collapsed with relict bedding; intercrystalline to breccia porosity.
187.1-192.6'	Tan very porous micrite; dissolutioned burrow porosity.

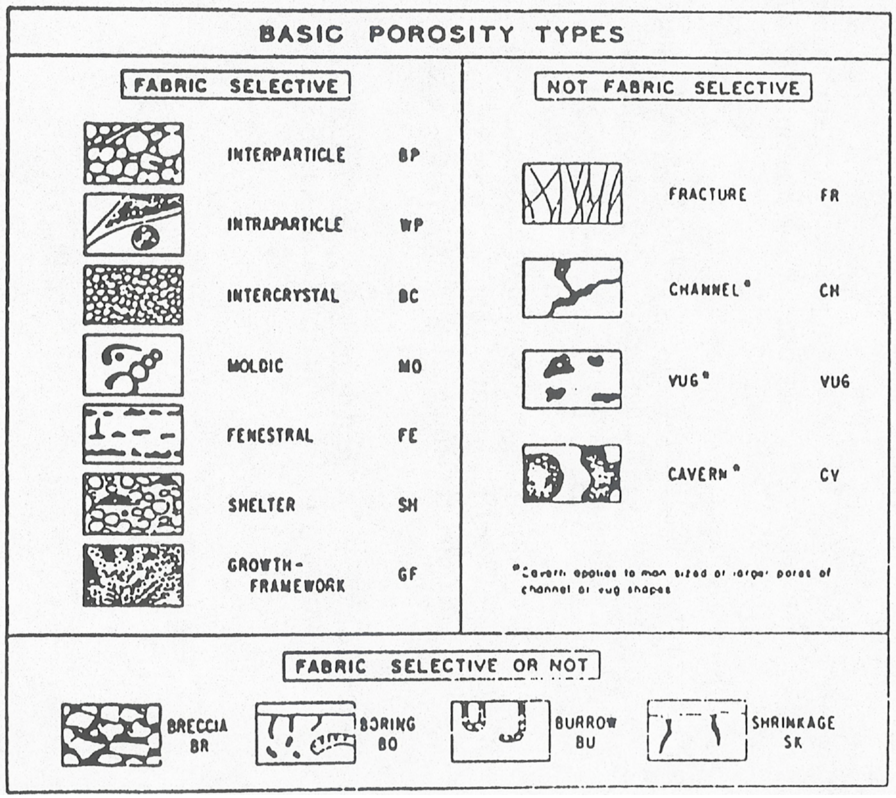


175.7–187.1′	Tan-brown punky to pulverulite micrite; collapsed; intercrystalline to breccia porosity.
172.8–175.7′	Tan-gray micrite; *Dictyoconus walnutensis* wackestone with some scattered mollusk fragments.
170.8–172.8′	Tan-gray punky to pulverulite micrite; intercrystalline porosity.
170.0–170.8′	Tan micrite with some FeO_2 staining.
167.8–170.0′	Light tan micrite; *miliolid* wackestone
165.6–167.8′	Light tan micrite; *miliolid* grainstone grading upward to a *miliolid* wackestone with some spar filled shell fragments.
163.8–165.6′	Tan-white pulverulite; intercrystalline porosity.
160.9–163.8′	Tan micrite with some FeO_2 staining; mudstone.
160.0–160.9′	Tan mottled micrite; mudstone.
159.2–160.0′	Tan micrite with some *miliolids* and FeO_2 staining.
154.0–159.2′	Tan micrite; some dissolutioned burrows, some infilled with chert; scattered *miliolids*; dissolutioned burrow porosity.
151.7–154.0′	Light tan micrite; *miliolid* wackestone with some spar replaced *Pelecypod* fragments.
150.2–151.7′	Light tan micrite with some scattered miliolids and spar replaced *Pelecypod* fragments.
149.0–150.2′	Tan micrite; mudstone, 2″ sparite seam @ 149.0′.
141.2–149.0′	Tan-gray vuggy micrite; good vuggy porosity.
133.1–141.2′	Light tan-gray micrite; mudstone with FeO_2 wispies (can appear to mimic the Regional Dense Member), very rythmic thin to medium beds.
129.1–133.1′	Tan-gray micrite; *Toucasia* and *Neithea* sp. wackestone with some *miliolids*.
123.9–129.1′	Tan punky to pulverulite micrite; intercrystalline porosity.
122.4–123.9′	Tan micrite with some FeO_2 wispies and *Toucasia* fragments, scattered *miliolids*.
118.3–122.4′	Light tan micrite with some spar replaced *Pelecypod* fragments.


Dolomitic Member
110'
100'
90'
80'
70'
60'
50'
112.9-118.3' Light tan allochem and miliolid grainstone to packstone; few black speoks (mollusk fragments or fecal material?) towards top.
94.7-112.9' Tan vuggy micrite; Dissolutioned Caprinid molds; some chert and Chondradonta; excellent moldic porosity.
88.5-94.7' Light tan-gray punky micrite; some chert.
85.6-88.5' Light tan micrite; miliolid grainstone to packstone.
77.2-85.6' Light tan micrite with scattered chert nodules.
75.7-77.2' Light tan vuggy micrite; vuggy porosity.
72.5-75.7' Light tan micrite
68.8-72.5' Tan vuggy micrite; vuggy porosity.
63.8-68.8'
60.9-63.8' Tan micrite; Turritella and shell fragment wackestone.
49.0-60.9' Marly, nodular micrite with Salenia sp., Texigryphea sp. and Ceratostreon texanum.
43.1-49.0' Inaccessible


Walnut Formation
Glen Rose Limestone
40'
30'
20'
10'
0
35.2-43.1' Marly, nodular micrite with Texigryphea sp.
26.0-35.2' Marly, nodular micrite with Texigryphea sp. and Ceratostreon texanum, some Turritella, Pelecypods, Echinoids, Neithea sp.
22.8-26.0' Dense micrite with shell fragments and some Ceratostreon texanum.
21.5-22.8' Burrowed micrite with Texigryphea sp some Pelecypod and Ceratostreon texanum; Turritella wackestone in lower half.
18.0-21.5' Dense micrite; miliolid grainstone with some Ceratostreon fragments. Bitumen styolite @ 18.5'
12.2-18.0' Burrowed micrite with Protocardia sp, Ceratostreon texanum; some Turritella and Gryphea sp.
8.9-12.2' Burrowed micrite with some Turritella.
5.2-8.9' Turritella wackestone with some Tylostoma sp, Echinoid and Echinoid spines.
0.0-5.2' Burrowed micrite with Ceratostreon texanum and some Turritella.
EXPLANATION
Bored surface
FeO2 wispies
Micrite clasts
Black specks (mollusk shell fragments or fecal material?)
Chert bed or chert nodules
Nodular bedding
Open porosity
Sparite concretions
Allochems
Miliolids
Dictyoconus walnutensis
Shell fragments
Pelecypods
Algal mat
Toucasia
Monopleura
Caprinid
Chondrodonta
Cladophyllia
Pleuromya knowltoni
Turritella
Protocardia sp.
Exogyra or Ceratostreon texanum
Neithea sp.
Texigryphea sp.
Echinoids
Change in location of section.

Depositional texture recognizable					Depositional texture not recognizable
Original components not bound together during deposition				Original components were bound together during deposition... as shown by intergrown skeletal matter, lamination contrary to gravity, or sediment-floored cavities that are roofed over by organic or questionably organic matter and are too large to be interstices.	Crystalline carbonate (Subdivide according to classifications designed to bear on physical texture or diagenesis.)
Contains mud (particles of clay and fine silt size)			Lacks mud and is grain-supported		
Mud-supported		Grain-supported			
Less than 10 percent grains	More than 10 percent grains				
Mudstone	Wackestone	Packstone	Grainstone	Boundstone	



Porosity-classification system of Choquette and Pray (1970)

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HAYS COUNTY GROUND-WATER DIVIDE

Excerpt from a report submitted to the
Edwards Underground Water District, December 1994

by
William G. Stein, LBG-Guyton Associates
1101 S. Capital of Texas Highway, Suite B-220, Austin, Texas 78746

Abstract

The ground-water mound that creates the divide generally west of Buda is the result of recharge the Edwards aquifer receives from surface water in Onion Creek. Recharge is focused in this area along Onion Creek because of extensive exposures of the Kirschberg evaporite member and numerous faults, which are favorable for the development of secondary porosity and permeability.

The Blanco River, located to the south, crosses primarily the upper Glen Rose and then the upper confining units after a narrow outcrop of Edwards. As a result, the Blanco River has less recharge potential than Onion Creek, even though the Blanco River has much higher base flows than Onion Creek. The recharge is focused in an area located along Onion Creek that has extensive exposures of Kirschberg evaporite member and numerous faults, which are favorable for the development of secondary porosity and permeability. The focused recharge in this hydrogeologically favorable area results in the mound, or high, in water levels that delineates the divide in the unconfined recharge zone.

In the artesian part of the aquifer, the divide is less defined. The water-level high may result solely from ground water discharging from the recharge zone to the confined section, such as a preferred flowpath that is directed from the Onion Creek area into the artesian part of the aquifer. It could possibly be modified by an unknown subsurface geologic structure. The water-level high in the artesian part of the aquifer between the Cities of Buda and Kyle is modified and possibly magnified by the effects of relatively larger amounts of pumpage in the vicinities of the two cities on either side of the high and the relative lack of pumping in the area between the two cities. Water levels measured toward the end of summer 1994 in the artesian part of the aquifer are below the level of San Marcos Springs Lake. These data may suggest that, during times of lower water levels, the artesian part of the aquifer generally north of the Blanco River may not supply water to San Marcos Springs but instead to pumpage near Kyle and Buda and to Barton Springs. A water-level high between Kyle and Buda that is shown by the summer 1994 measurements indicates that flow during this period does not move past San Marcos Springs to Barton Springs.

Based on the data in this report, the ground-water divide in Hays County should be located generally between the Cities of Buda and Kyle in the artesian part of the aquifer and then along Onion Creek in the Edwards aquifer recharge zone. Given the configuration of the water table and location of the high in water levels over this area, water recharged along Onion Creek would go to both Barton Springs and San Marcos Springs. Even though ground-water divides are drawn along water-level highs, the certainty of the boundary for flow to move only in one direction away from the ground-water high is unknown. This may be especially true given that the Edwards aquifer is a karst limestone and flowpaths may not always follow the apparent gradient on a contoured water-level map because of the associated caves and fractures. Different conditions may cause different flowpaths within the Edwards aquifer.

Introduction

This excerpt is from a report that presented the results from a study made by LBG-Guyton Associates with assistance from the Edwards Underground Water District to evaluate and better delineate the ground-water divides that form the western and eastern limits of the Edwards aquifer. The following discussion focuses on the eastern divide in Hays County.

Hays County is located on the very northeastern end of the Edwards (Balcones fault zone) aquifer in the San Antonio region. The portion of the Edwards aquifer to the north of the Hays County ground-water divide is known as the Austin region of the Edwards aquifer. The area between these two portions of the aquifer has been referred to as the Hays County ground-water divide.

Water levels in the Edwards aquifer are affected by the amount of water the aquifer receives from recharge as a result of precipitation, infiltration of streamflow and the amount of water taken from the aquifer as result of pumping from wells and springflow. Precipitation at San Marcos, Texas has averaged 33.79 inches per year for the

91-year period of record through 1992 (Bader and others, 1993).

The major sources of discharge to the aquifer in this area are San Marcos Springs and Barton Springs, located south and north of the study area, respectively. Annual mean discharge from San Marcos Springs is 170 cubic feet per second (cfs) (about 123,000 ac-ft/yr) for the period of record, 1957 to 1993 (USGS, 1994). For Barton Springs, the annual mean discharge is 63.4 cfs (about 46,000 ac-ft/yr) for the period of record, 1978 to 1993 (USGS, 1994).

Pumping centers exist near the Cities of Buda and Kyle where public supply wells and a higher density of domestic wells are located. The public supply pumpage for the City of Buda has increased from 43 ac-ft/yr in 1955 to over 230 ac-ft/yr in 1993. Additionally, Goforth Water Supply Corporation, in close proximity to the City of Buda, has a well field that has been producing up to 400 ac-ft/yr since the mid-1980's (BSEACD, written communication, 1994). In Kyle, the pumpage has increased from 84 ac-ft/yr to over 582 ac-ft/yr from 1955 to 1993.

Analysis of Water-Level Data

Previous delineations of the ground-water divide in Hays County appear to have varied. Hearings before the Texas Water Commission (now TNRCC) for the creation of the Barton Springs/Edwards Aquifer Conservation District (BSEACD) demonstrated that, based on previous work, the ground-water divide in Hays County appeared to have shifted over time generally between the Cities of Kyle and Buda. In earlier studies, the Hays County ground-water divide was determined from potentiometric-surface maps with as few as three measured water-level control points within the area of interest. The approximate locations of the ground-water divide from previous studies are shown in Figure 1. The dates of the water-level measurements and the authors of the respective reports are referenced in the figure. The shift in the location of the divide may be caused by the lack of data control for drawing the potentiometric contours, because only a few data points were used, or by different wells being used for water-level data points for different maps. In order to confirm the location of the divide, water levels in a larger number of wells needed to be measured "simultaneously." This was done by reevaluating the data collected by EUWD and TWDB in 1985, as well as measuring water levels in wells in the winter and summer of 1994.

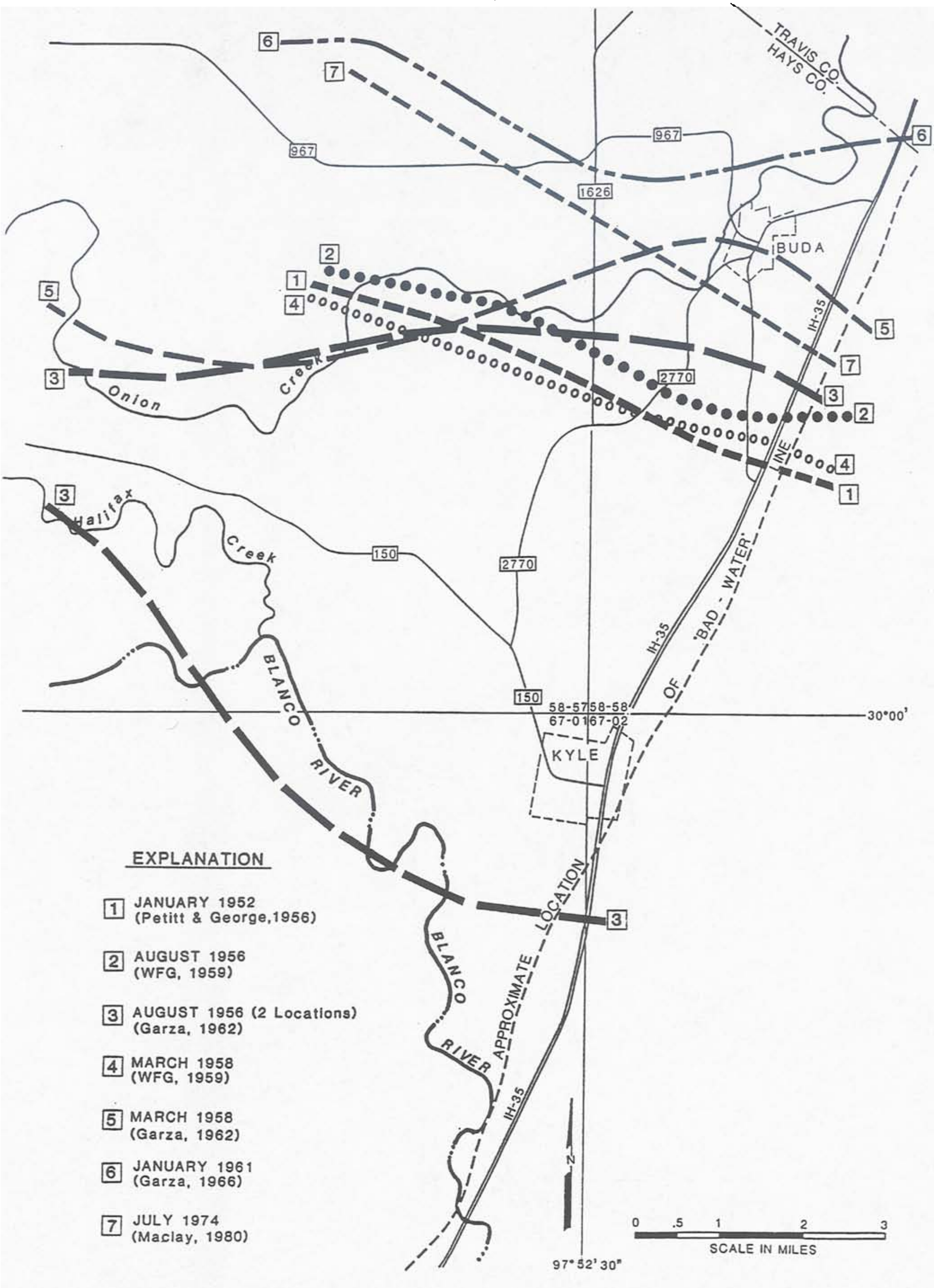
Water-level data collected by the EUWD and TWDB in 1985 for the delineation of the BSEACD was reevaluated, and the results are presented in Figure 2. Based on the recent surface hydrogeologic mapping, some wells on the western end of the selected well set are believed to be completed in the Glen Rose. Therefore, these wells were not used in reevaluating and plotting the 1985 water levels. Near average precipitation of 33.54 inches (Bader and others, 1993) occurred at San Marcos during 1985, indicating that water-level conditions in this area were also probably under average conditions.

LBG-Guyton Associates measured water levels in the winter (January and February) and water levels in late summer (August and September) of 1994. Data are shown on Figures 3 and 4. Prominent water-level highs can be seen on both winter and late summer 1994 water-level maps in the vicinity of Onion Creek. The rainfall conditions during the period before the water-level measurements taken in late August and early September were initially very dry, but several heavy rains occurred a few weeks just prior to the time the measurements were made. In Austin, the month of August was one of the wettest Augusts on record. What exactly might happen to the water-level high along Onion Creek over extended dry periods is not clearly understood.

Water levels in the artesian part of the aquifer were relatively flat in February 1994, but there was a high between the Cities of Buda and Kyle. Other than possible hydrogeologic factors, the location of this high in water levels may be associated with relatively high pumping centers in the vicinities of Kyle and Buda on either side of the high and the relative lack of pumping in the area between the two cities. The pumpage in the cities would cause cones of depression during heavy pumping and a corresponding high between the two pumping centers.

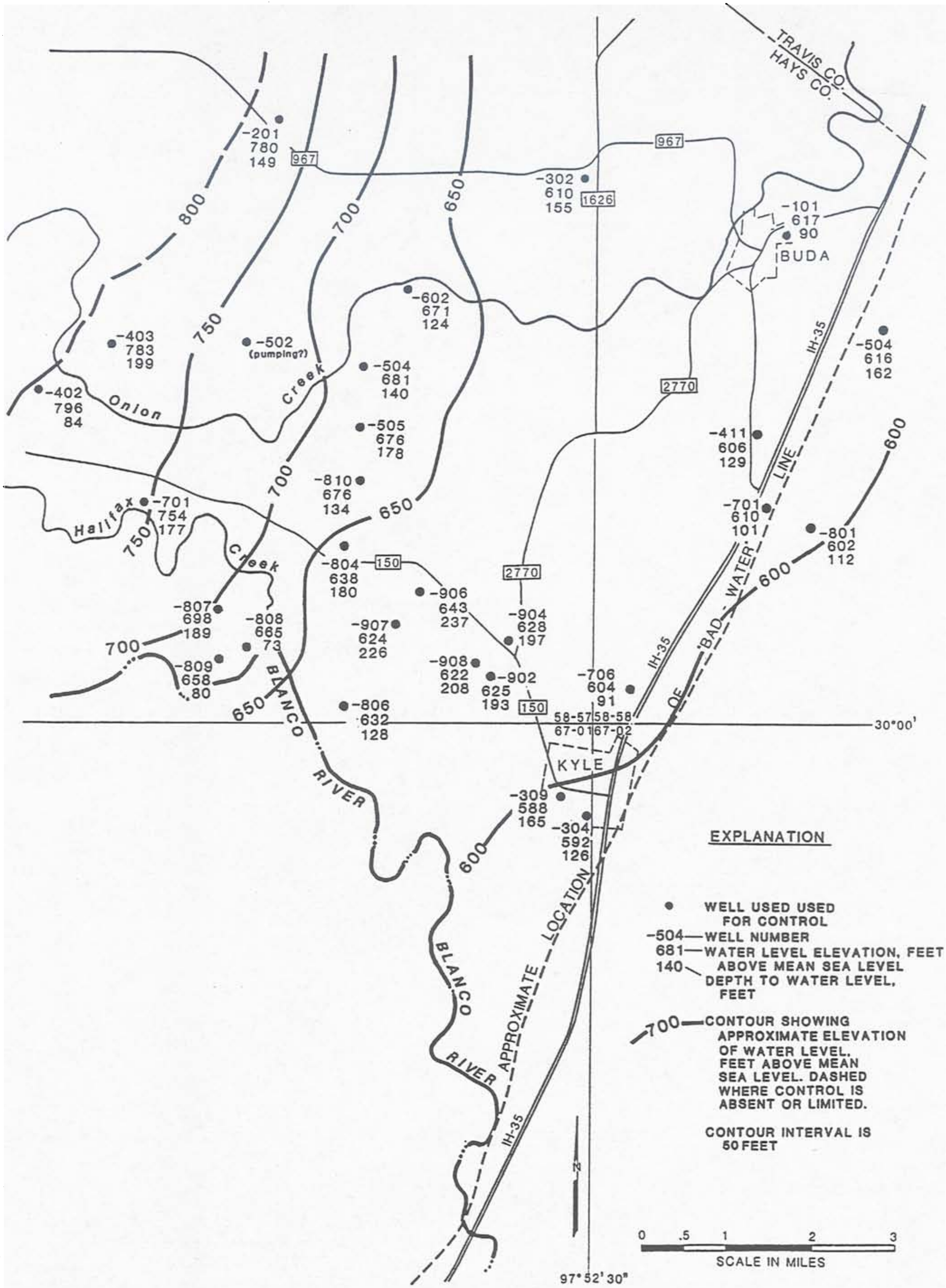
The elevation of water levels throughout the study area in early 1994 was higher than the elevation of San Marcos Springs Lake at 575 feet above mean sea level. However, during the second set of 1994 water-level measurements, levels for much of the artesian part of the aquifer from just south of Kyle through Buda dropped below the San Marcos Springs Lake level. The late summer water levels may indicate that ground water is not flowing toward San Marcos Springs during lower water-level conditions, but supplying pumpage at Kyle, Buda and areas toward Barton Springs instead. The elevation of Barton Springs, 432 feet above mean sea level, is much lower than water-level elevations in the Buda/Kyle area. A water-level high still remains during the summer measurements, which indicates that ground-water flow does not move from San Marcos Springs toward Barton Springs at this time.

Water levels in this artesian area are subject to declines caused by pumping as evidenced by water levels fluctuating up to 40 feet in magnitude during a single day, which can be seen in the BSEACD observation well in



APPROXIMATE LOCATIONS OF PREVIOUSLY DELINEATED GROUND-WATER DIVIDES IN HAYS COUNTY

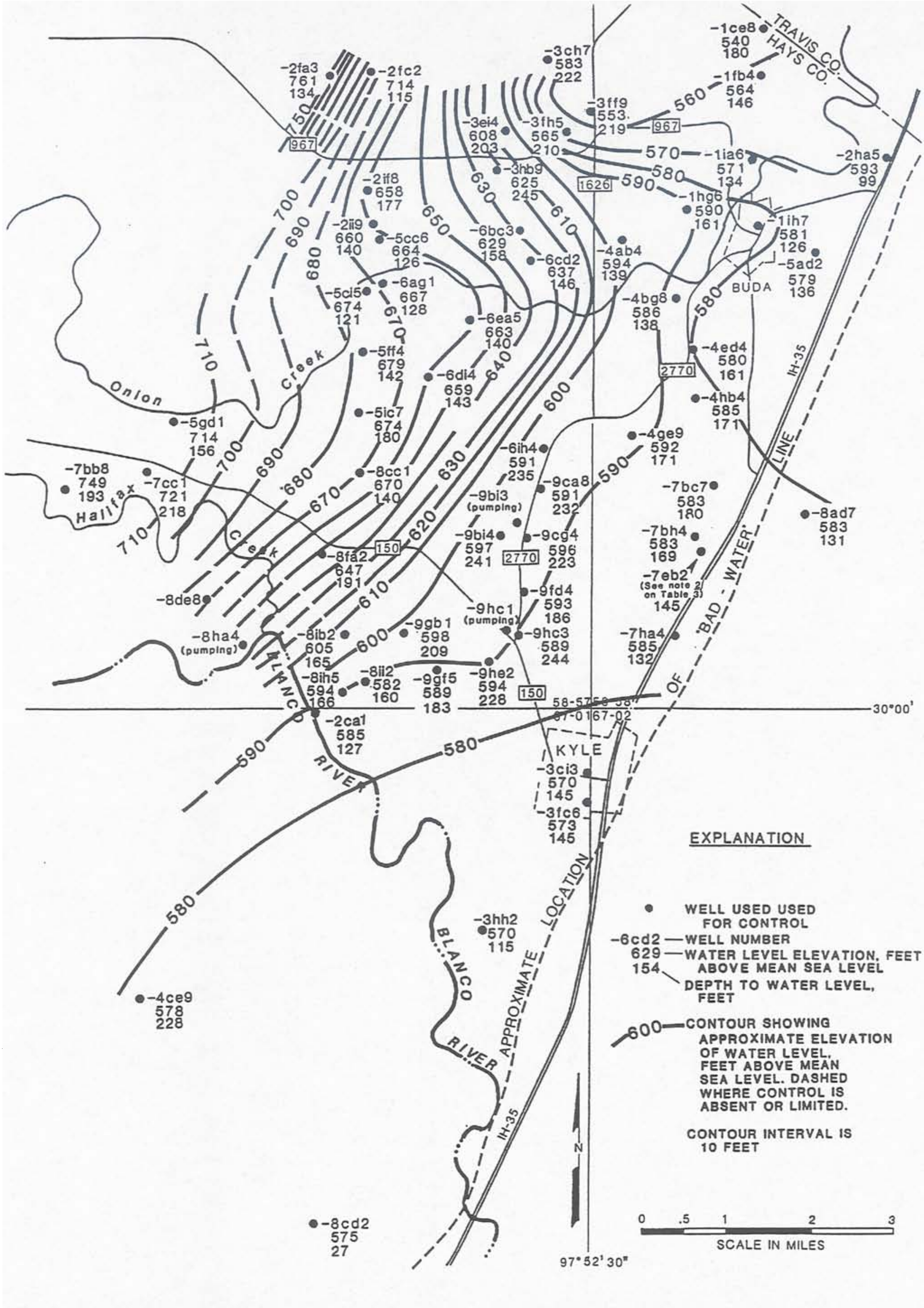
FIGURE 1



APPROXIMATE ELEVATION OF AND DEPTH TO WATER LEVELS IN THE EDWARDS AQUIFER, HAYS COUNTY (JULY AND AUGUST, 1985)

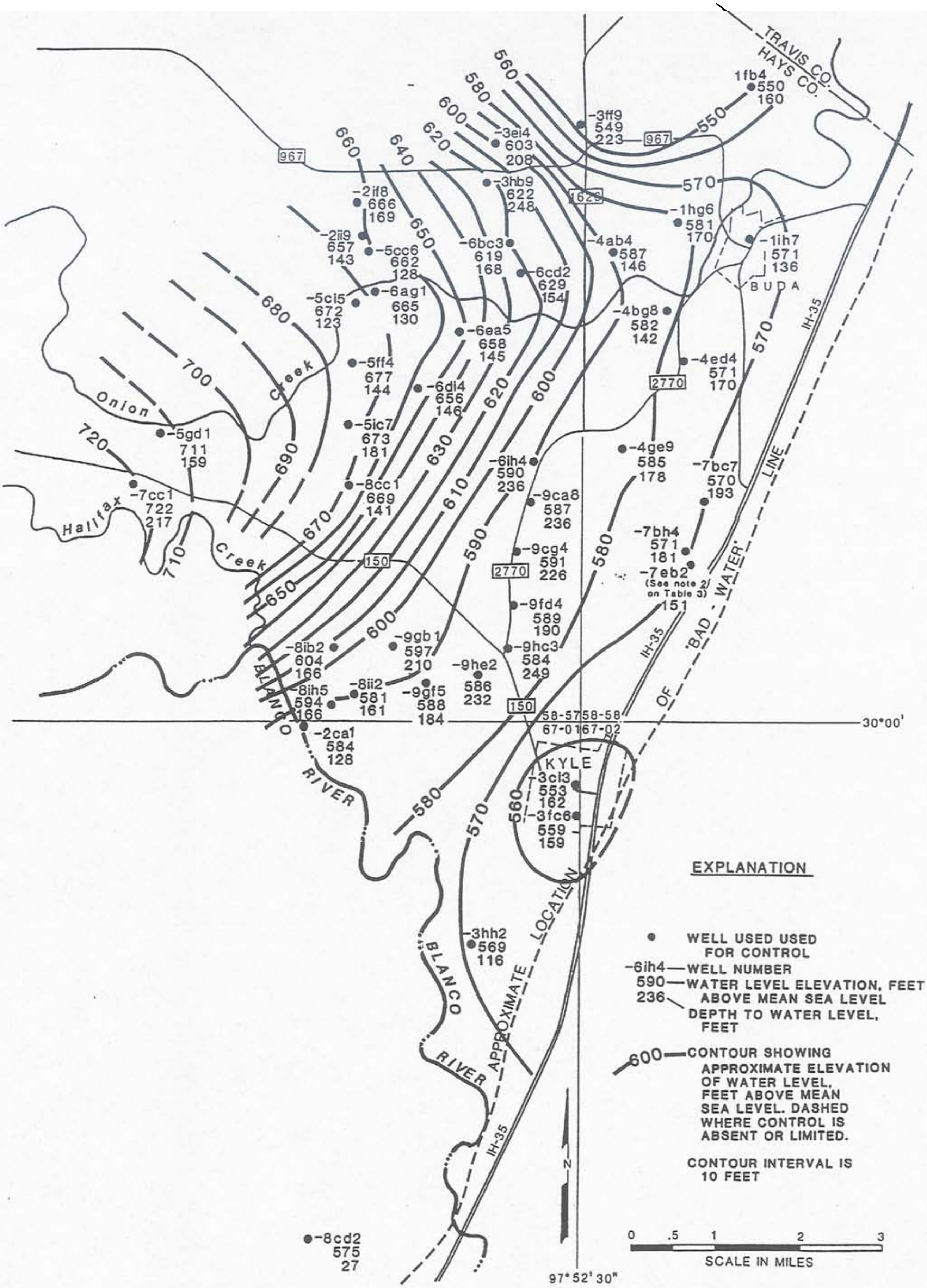
FIGURE 2

LBG-GUYTON ASSOCIATES



APPROXIMATE ELEVATION OF AND DEPTH TO WATER LEVELS IN THE EDWARDS AQUIFER, HAYS COUNTY (JANUARY AND FEBRUARY, 1994)

FIGURE 3



APPROXIMATE ELEVATION OF AND DEPTH TO WATER LEVELS IN THE EDWARDS AQUIFER, HAYS COUNTY (AUGUST AND SEPTEMBER, 1994)

FIGURE 4

Buda (LR-58-58-101) (S. Vickers, oral communication, 1994). For the period of record provided by continuous water-level recorders maintained by BSEACD and EUWD, generally from late 1991 to the present, the highest water levels in these wells occurred in June 1992 and the lowest occurred in late July to early August 1994. Daily water-level highs have fluctuated over 80 feet in Well LR-58-58-101 and over 60 feet in Wells LR-58-57-9bi4 and LR-67-01-303 (Figure 5).

Changes in water levels from winter to summer 1994 in the north-northeast Hays County area are shown on Figure 10. A lowering of water levels is shown for all the wells except two. The two wells that showed rises in water levels are believed to be associated with the effect of local pumpage at the time of the winter water-level measurements. The greatest declines generally are in the artesian section and may be focused on the Cities of Buda and Kyle in association with relatively higher pumpage. The other area that experienced large water-level declines between winter and summer of 1994 is along the east end of the recharge zone along Onion Creek.

Geologic and Hydrologic Features

The study area in Hays County is composed predominantly of Cretaceous strata as discussed earlier in the Regional Geology section. The Glen Rose Limestone and the Austin Chalk also form aquifers in the Hays County area, but the Edwards limestone is the principal aquifer of interest to this study. The area also has minor deposits of more recent alluvium found mostly within the floodplains of the Blanco River and smaller creeks.

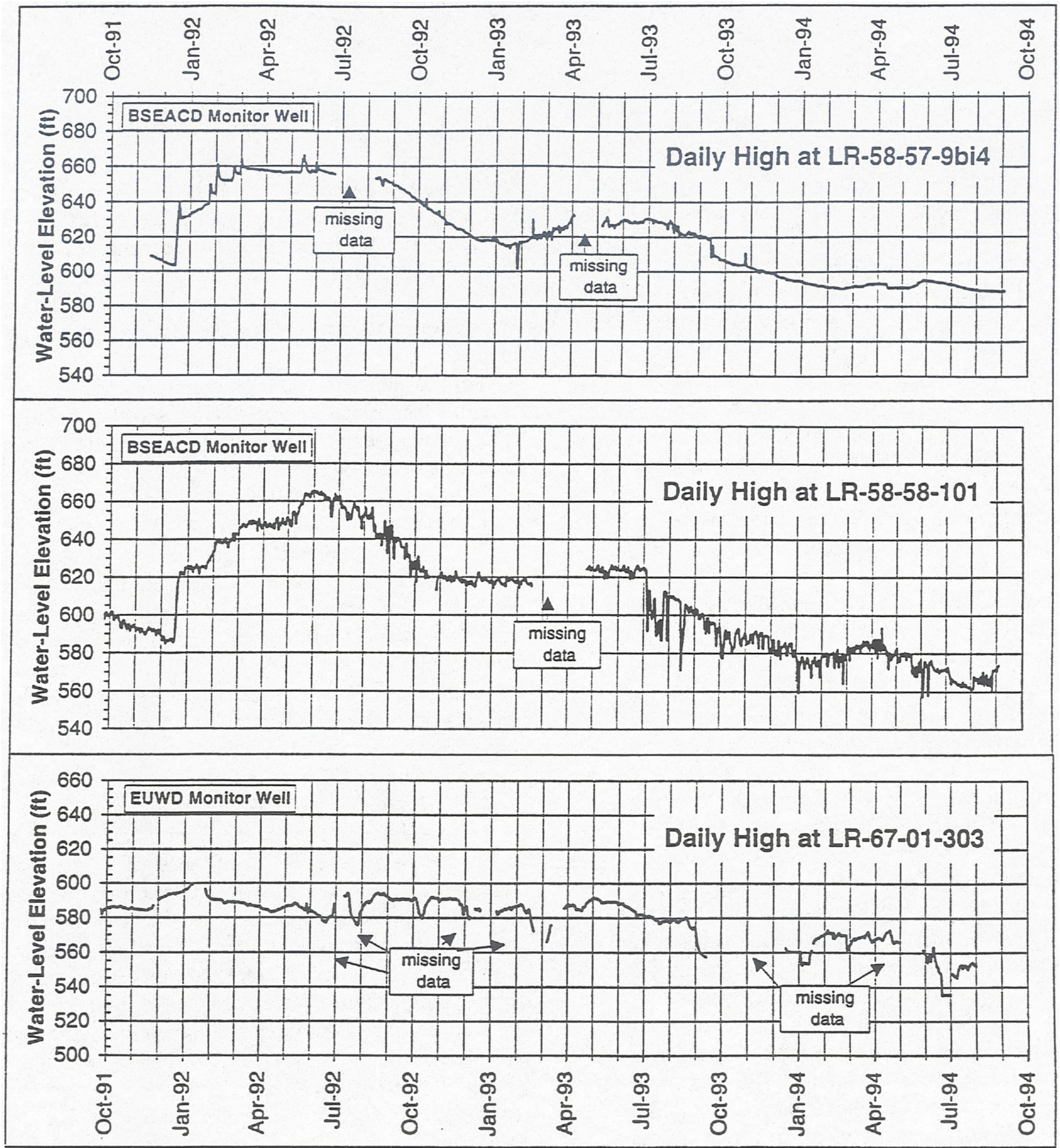
The dip of the Cretaceous rocks in the study area is between 10 and 15 feet per mile to the southeast in the downdip direction (Arnow, 1959). This creates a hydrogeologic setting that permits ground water to flow toward the southeast, generally toward San Marcos Springs from the area northwest of the springs. In contrast, faults in Hays County primarily trend N40° to 50°E. The fault zones have associated fracturing that causes locally increased porosity and permeability. Conduits developed as a result of this may direct flow generally along the fault trends toward Barton Springs from the north-central Hays County area rather than to the southeast with the dip of the rocks.

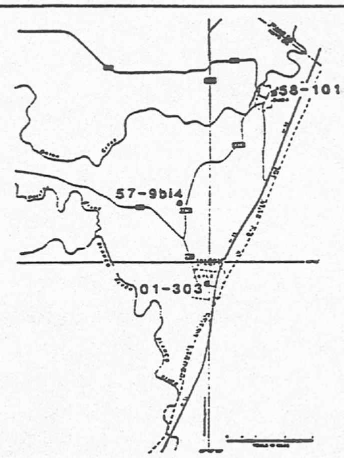
A recent series of USGS mapping projects in the Edwards aquifer recharge zone, starting in Bexar County (Stein and Ozuna, unpub.), moving northward through Comal County (Small and Hanson, unpub.) and Hays County (Hanson and Small, unpub.) and currently underway in southern Travis County, have given a more detailed hydrogeologic picture of the recharge zone. A part of the mapping in Hays County (Hanson and Small, written communication, 1994) generally north of Onion Creek to south of Blanco River is shown in Figure 7. West of Mustang Branch Fault is the Edwards aquifer recharge zone (Figure 7), and east of the fault the surface geology generally consists of the sequence of Del Rio Clay, Buda Limestone, Eagle Ford Shale (upper confining unit) and Austin Chalk, with some minor recent alluvial deposits veneering the creek areas not being depicted on the map.

Several interesting geologic conditions can be inferred from this mapping. A series of faults with generally the basal nodular member on the south side of the faults and the leached/collapsed members on the north side of the faults are present north of the Blanco River in the southwest corner of quadrangle 58-57. These faults, which have approximately 250 feet of displacement, possibly act as barrier faults that isolate flow within the respective blocks. South of the fault, such a small remnant of the Edwards section remains that only the basal nodular member and some of the dolomitic member crown the tops of hills. Thus, any water recharged over Edwards outcrop, south of the fault, probably would not stay in Edwards strata but have a water table near the contact with or even within the upper member of the Glen Rose Limestone.

Only a limited reach of the Blanco River is actually on Edwards limestone. Most of the reach of the river is on upper Glen Rose. Downstream the river crosses predominantly the basal nodular member and some of the dolomitic member (lower Kainer Formation), and finally two smaller fault blocks of upper Person Formation. The upper confining unit (Eagle Ford Shale, Buda Limestone and Del Rio Clay) is exposed predominantly in the Blanco River bed between the two fault block areas, where upper Person Formation is exposed, and again further downstream. As a result of the limited number of river miles with Edwards exposure, the Blanco River has a diminished potential for recharging the Edwards aquifer.

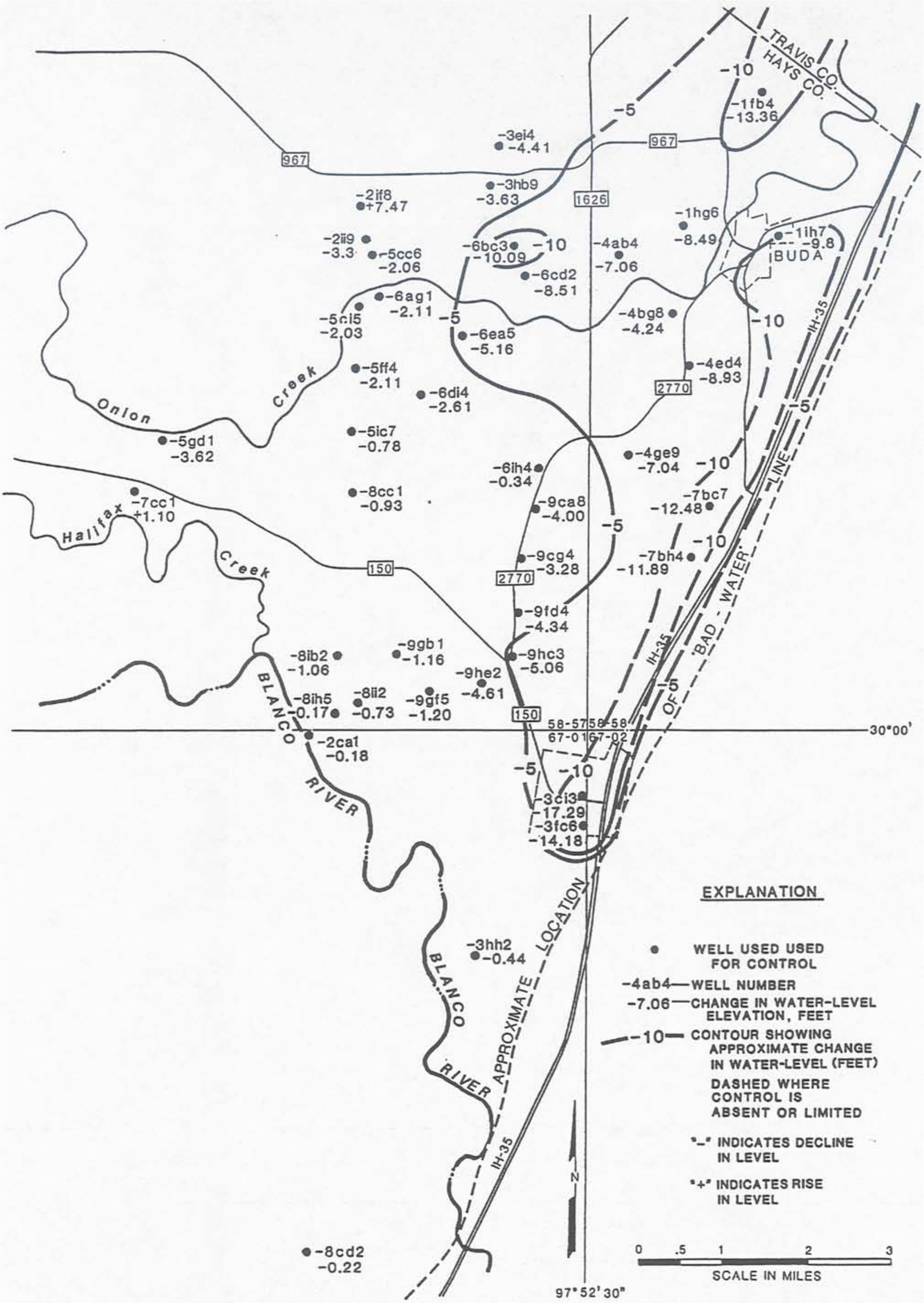
On the other hand, Onion Creek, which is located to the north of the Blanco River, has optimal hydrogeologic conditions for recharging the aquifer even though the quantity of base flow is much less than the base flow for the Blanco River. North of FM Road 150, Onion Creek flows over a long stretch of the exposed Kirschberg evaporite member, which hydrostratigraphically has the highest potential for development of secondary porosity and the resulting increased transmissivity (Stein, 1993). Also, toward the lower end of this stretch, Onion Creek crosses several faults including one that trends parallel to the creek at about N35°E. The focused recharge of surface water undersaturated with respect to calcium carbonate within Onion Creek would accelerate dissolving of the faulted rock and Kirschberg evaporite to form





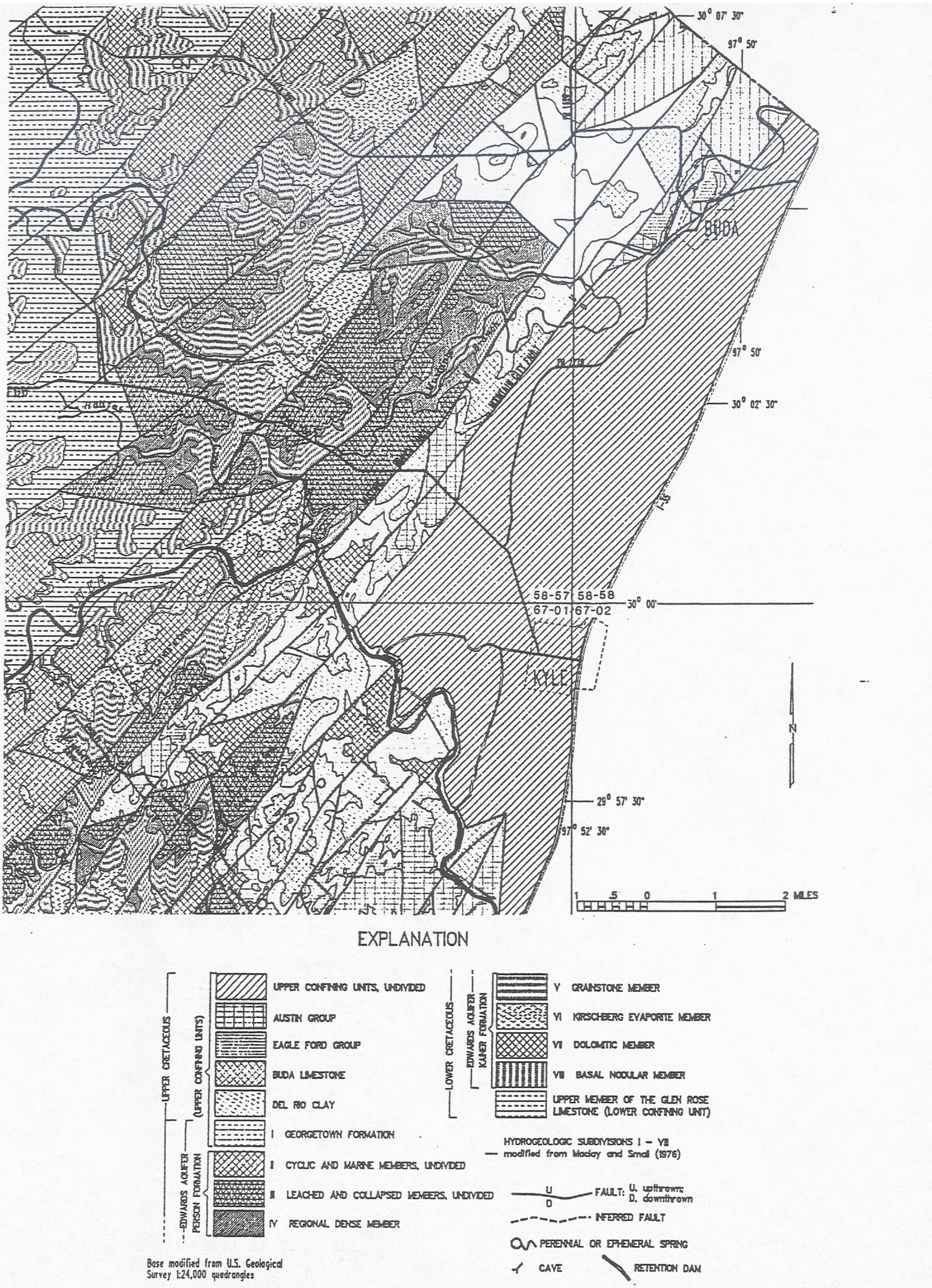
DAILY WATER-LEVEL HIGHS IN SELECTED MONITOR WELLS
MAINTAINED BY THE BSEACD AND EUWD IN HAYS COUNTY

FIGURE 5



CHANGES IN WATER LEVELS IN HAYS COUNTY WELLS MEASURED IN EARLY 1994 AND LATE SUMMER 1994

FIGURE 6



GEOLOGIC MAP OF HAYS COUNTY GROUND-WATER DIVIDE AREA
(HANSON AND SMALL, WRITTEN COMMUNICATION, 1994)

FIGURE 7

extensive secondary porosity. This enhanced recharge potential along Onion Creek appears to cause the ground-water high that delineates the ground-water divide in the Edwards aquifer recharge zone in Hays County.

The BSEACD is planning to conduct a dye tracer test in Antioch Cave located in the stream bed of Onion Creek about 1.6 miles upstream of FM Road 967 near Buda. Hopefully, this dye trace study will more accurately determine specific flowpaths in this part of the Edwards aquifer.

Fairly constant inflow from upstream into a small reservoir located at the north end of this stretch of Onion Creek within the Edwards outcrop provides a source of relatively continuous recharge to the Edwards aquifer. Discharge records are available for Onion Creek near Driftwood and downstream of the Edwards aquifer recharge zone near the City of Buda. The difference between the two gages indicates the potential recharge to the aquifer. On occasion, rainfall and runoff occur between the gages resulting in discharges at Buda being higher than discharges at Driftwood, which results in a negative number for the potential recharge. Additionally, some of the negative values in the upstream minus downstream are associated with storm runoff pulses arriving at the downstream gage the day after the pulse passes the upper gage.

For comparison, the difference between the upstream gaging station on the Blanco River near Wimberley, Texas and the downstream gaging station near Kyle, Texas suggests that only minor recharge occurred within that reach. The major negative discharge differences on the Blanco River probably are associated with the time-delay of runoff, as mentioned above for Onion Creek, and not from recharge. This supports the geologic observations that much of the Blanco River exhibits limited recharge potential.

Large water-level declines occurred between winter and summer 1994 (Figure 6) along the east end of the recharge zone along Onion Creek. The aquifer is confined in some of this area where outcrops of Del Rio Clay occur, but the aquifer is generally under water-table conditions with the water level being below the contact between the Edwards limestone and the Del Rio Clay. The areas along Onion Creek probably have the best enhanced secondary porosity as compared to areas further away from the creek. As a result, this area along the creek has the highest relative permeability and is capable of transmitting water away the quickest. The large fluctuations in water level in this area may result from this. The continuous recharge source located upstream along Onion Creek cannot supply as much water to this area as can be transmitted away during drier times. Another possible reason for the drop in water level in this area is that a cone of depression associated with pumpage near the City of Buda may spread up into this more transmissive area along Onion Creek first before moving into the surrounding tighter limestone.

In the updip limits of the recharge zone, the hydrostratigraphy plays a very important role in controlling the depth of the water levels. According to well owners and a review of available data, the water levels in many wells located near the updip limit of the recharge zone would drop to a particular level during dry times and then stop declining. By comparing the recent hydrogeologic mapping and known thickness of aquifer units to the depth of the well, many of the wells in the western part of the recharge zone in Hays County appear to bottom in or below the basal nodular member; that is, near the contact between the Edwards limestone and the upper member of the Glen Rose Limestone. In the recharge zone, the basal nodular member often exhibits large secondary porosity development and numerous caves, which may be associated with dissolution occurring above the perching of the underlying upper Glen Rose Limestone (Stein, 1993). In this area of the recharge zone where the Person Formation has been stripped off, the basal nodular member may be the most reliable and ultimate water-producing unit because of the perching effects of the less transmissive underlying upper Glen Rose Limestone. During lower water-level conditions, the depth and location of the basal nodular member from land surface may dictate the water levels in the recharge zone.

The ground-water divide in the confined section of the aquifer could be controlled by the structural setting or the hydrologic setting. The water-level high in the artesian section may result because of a preferred pathway from the mounding of ground water beneath Onion Creek in the recharge zone into the artesian part of the aquifer. Another possibility is that, based on topography, a structural high exists between the Cities of Kyle and Buda.

Austin Chalk is on the surface over much of the artesian part of the aquifer in this area, which is located generally near IH 35 between the Cities of Kyle and Buda. Available electric logs show the Edwards aquifer is about 340 to 410 feet below the land surface in this part of the study area. However, not enough electric logs from wells drilled between the Cities of Kyle and Buda were available to develop a complete detailed geologic picture of the Edwards aquifer in the subsurface. A topographically high ridge between Loop 4 and IH 35, south of the City of Buda, is close to the location of the ground-water divide and may reflect some subsurface structure causing the ground-water divide in the artesian part of the aquifer.

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GROUNDWATER USAGE FROM THE BARTON SPRINGS SEGMENT OF THE EDWARDS AQUIFER

by

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Donald G. Rauschuber, Donald G. Rauschuber & Associates, Inc.

This paper characterizes water use and demand in the Barton Springs segment of the Edwards aquifer. The Barton Springs/Edwards Aquifer Conservation District (District) is charged by the State of Texas with the preservation, conservation, and protection of the Barton Springs segment of the Edwards aquifer and other groundwater located within its jurisdictional boundaries. To help meet these goals the District monitors permitted groundwater use and major spring discharges.

Permits are issued for public water supply, industrial, irrigation, and commercial wells. Permits also authorize the withdrawal of specific amounts of groundwater, and require permittees to submit monthly pumpage reports (Rules and Bylaws, 1993). The following wells do not require a permit, and subsequently do not submit monthly pumpage reports: 1) wells incapable of producing more than 10,000 gallons per day; 2) wells used to satisfy the domestic needs of five or fewer households; 3) agricultural wells used for non commercial livestock and poultry operations, in connection with a farming, ranching, or dairy operation.

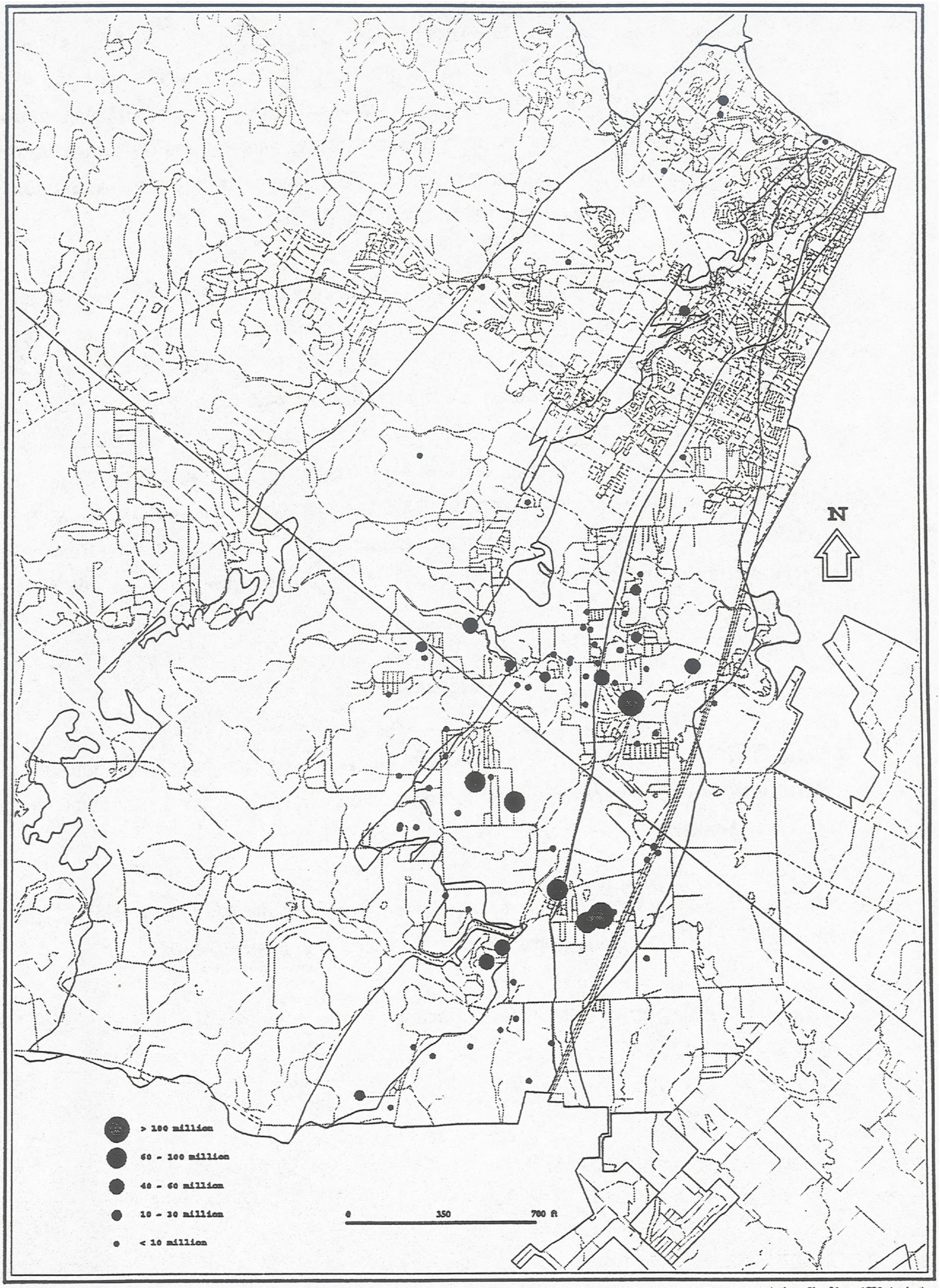
Public water supply wells use the majority of permitted groundwater withdrawn from the Barton Springs segment of the Edwards aquifer. They accounted for 82% of the permitted use in 1994. The remainder is withdrawn by industrial, commercial, and irrigation wells. Table 1 describes the type of permitted use, number of users, volume, and percent use. The distribution of permitted wells or well systems (pumpage greater than zero) along with their relative groundwater use in 1994 is illustrated on Figure 1.

Non-permitted domestic wells were estimated in 1988 to number approximately 1475 (Brandes, 1988). From 1988 through August 1994, another 85 non-permitted domestic wells were drilled. Per capita consumption for individuals using domestic wells in our segment of the Edwards aquifer is estimated at 170 gallons/person/day. Using this figure, combined with the number of non-permitted domestic wells (1560), yields a total of

TABLE 1 - Permitted Water Use			
Type of Use	Number	Volume	Percent
Public Water Supply	43	917,509,833	82%
Irrigation	9	65,865,309	6%
Industry	8	104,340,335	9%
Commercial	22	30,944,810	3%
Total		1,118,660,287	100%

FIGURE 1

1994 Permitted Pumpage Distribution



Barton Springs/Edwards Aquifer Conservation District

Author: Shu Liang (GIS Analyst)

approximately 339,000,000 million gallons withdrawn by non-permitted domestic wells in 1994.

Combined use from permitted and non-permitted domestic wells totaled approximately 1,457,660,287 gallons. Agricultural withdrawals are not reported to the District; however, estimated use ranges from 13,000,000 to 16,000,000 gallons (BS/EACD, 1990). In 1994, non-permitted domestic wells accounted for approximately 23%, agricultural wells accounted for approximately 3%, and permitted wells accounted for approximately 74% of the total water withdrawn from the aquifer.

On June 25, Barton Springs discharge reached its lowest point in 1994, 16.5 cfs, and remained at this level for several days. Low-flow conditions were a response to below average rainfall. Under these low-flow conditions, groundwater withdrawals from wells used for non-agricultural purposes may account for at least 74% of the total daily discharge from the aquifer. Adjustments for increased summer demand could significantly increase the total daily discharge percentage from wells used for non-agricultural purposes. Groundwater demand from wells contributes significantly to total discharge from the Barton Springs segment of the Edwards aquifer. Its relative importance to the groundwater balance is variable, but is especially important during prolonged periods with little or no rainfall.

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Localization of Sediment and Trace Metals along a Karst Conduit Flow Route in the Barton Springs Segment of the Edwards Aquifer

by

Nico M. Hauwert, Barton Springs/Edwards Aquifer Conservation District

The results presented in this paper are based on hydrogeologic data collected by U.S. Geological Survey (USGS) during the 1980's, hydrogeologic data collected by the Barton Springs/Edwards Aquifer Conservation District (BS/EACD) in the early 1990's, and preliminary geologic data compiled as a cooperative mapping effort between the USGS and BS/EACD. Both of the BS/EACD studies were funded in part by the Texas Water Development Board (TWDB). The Edwards Underground Water District and the TWDB graciously supplied geophysical logs that were utilized in the geological interpretation. Much of this paper is taken from a report by the Barton Springs/Edwards Aquifer Conservation District entitled The Barton Springs/Edwards Aquifer: Hydrogeology and Water Quality.

Geologic Influences on Development of Groundwater Flow Conduits

Two factors, the vertical distribution of soluble rock layers and lateral distribution of geologic structure, seem to be key in the formation of solution cavities and caves that distinquish the Edwards as a karst aquifer. The Edwards aquifer consists of several members which are based on stratigraphy and permeability (Rose (1972), and Maclay and Small (1984)). The hydrostratigraphic units of the Edwards Group and adjacent formations in the Barton Springs Segment are shown in Figure 1. In Travis County, the Edwards Group thins significantly toward the Colorado River as a result of erosion or nondeposition of the Marine and Leached Members below the Georgetown Formation. In the Austin area, cave are commonly well-developed in the Leached, Collapsed, Grainstone, and Kirschberg Members (Russell, 1987). The Georgetown, Regional Dense Member, the Walnut Formation, and the upper 200 feet of the Glen Rose generally do not promote extensive horizontal cavernous development. The Basal Nodular Member can be a relatively permeable member in the San Antonio area, but grades into a less permeable Walnut Formation in the Austin area (John Hanson, personal communication, 1995). Vertical pits have been observed in Austin-area caves that breach the Georgetown Formation, Regional Dense Member, and Walnut Formation (Russell, 1994, personal

Group	Formation	Member	Rhodda's Member Equivilent	Austin Thickness (Travis Co.) (feet)	Platform Thickness (Hays Co.) (feet)
Washita	Georgetown			40-60	50
Edwards	Person	Marine	1	0	150-90
		Leached-Collapsed	1	20-90	90
		Regional Dense	2	20-30	22-25
	Kainer	Grainstone	3	45-60	50-60
		Kirschberg	4	70	50-60
		Dolomitic	4	133	130
	Walnut			65	45-60
Trinity	Glen Rose				

Revised from Maclay and Small, 1984, and preliminary observations reported by John Hanson, USGS. The thicknesses reported here may be futher delineated in future reports.

Hydrostratigraphic Units of the Edwards Group and Associated Formations and Their Approximate Thicknesses

Barton Springs/Edwards Aquifer Geological Mapping Study

Figure 1

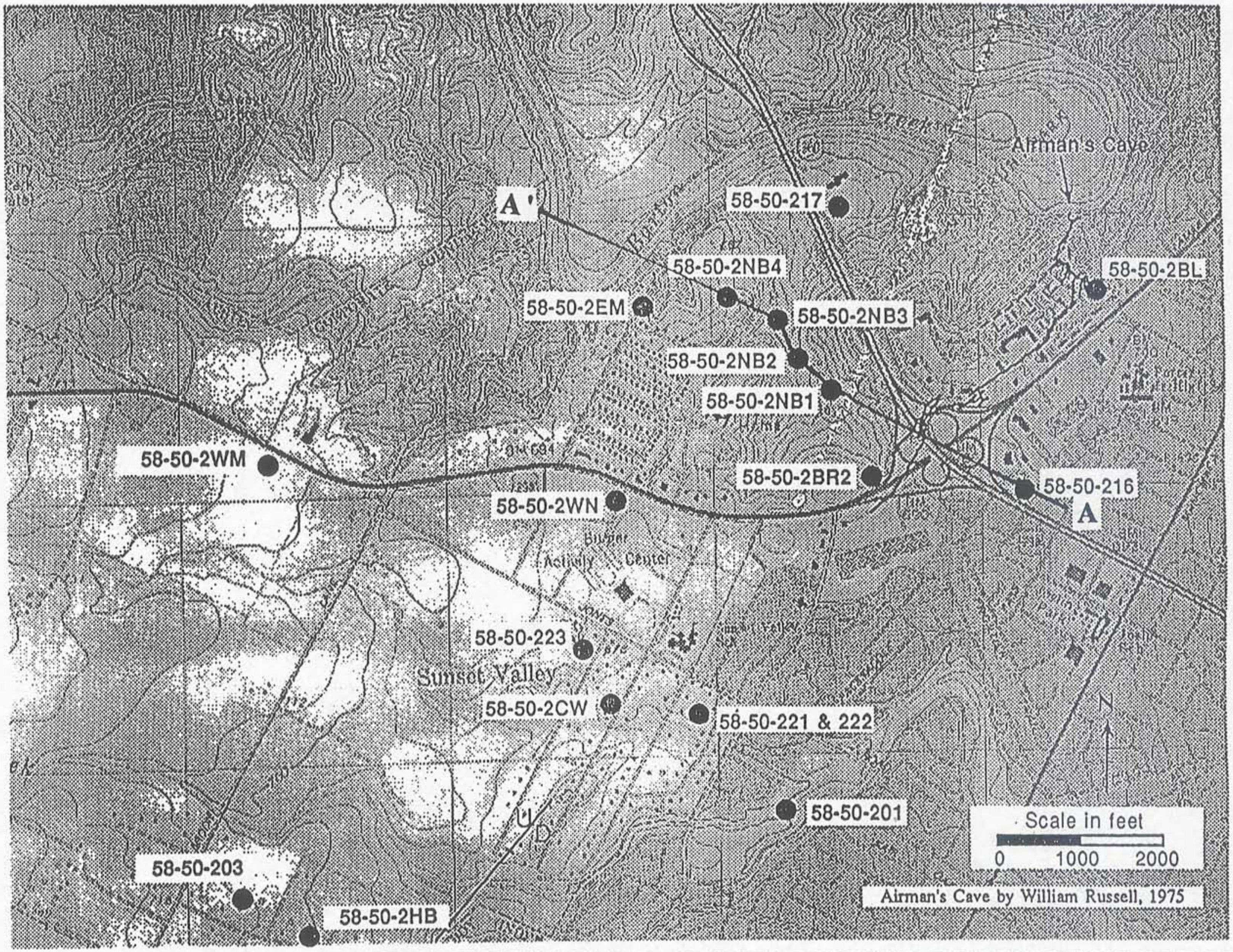
communication).

Solution-cavity development appears to be localized along geologic structures, such as faults and fractures within the Barton Springs segment. Water-level data collected by the USGS shows that drawdown associated with the draining of the Barton Springs pool extends at least three miles along the direction of faulting. This decline is only visible during low-flow conditions when hydraulic gradient is less steep (Raymond Slade, 1993, USGS, personal communication). No drawdown was observed in an observation well 0.6 miles from the pool, in a direction perpendicular to faulting. Water-level measurements collected by the Barton Springs/Edwards Aquifer Conservation District show a trough in the potentiometric surface that parallels faulting in the area (Figures 2 and 3). Studies by Thrailkill (1985) and Quinlan (1990) in Kentucky indicate that preferred conduit flow routes tend to show potentiometric troughs, analogous to combinations of minor surface drainages into a surface stream. This trough in the water table parallels faults that trend toward Barton Springs. This suspected flow route, called the "Sunset Valley flow route," subparallels a previous abandoned subsurface flow route, Airman's Cave. Figure 4 shows a geologic cross section across the Sunset Valley flow route, based on geophysical logs and surface mapping. The groundwater flow system is expected to be an integrated, water-saturated cave network developed within the Kirschberg Member that roughly parallels local faults. Groundwater tracing is needed to verify and further characterize this possible flow route to Barton Springs.

Airman's Cave is a good model to observe how conduits formed to create a subsurface flow system (see Figure 3). The two-miles of mapped passages are restricted to the Leached and Collapsed Members of the Edwards Group. The cave parallels at least two faults, and its passage segments strongly follow joints. The cave is normally dry now although in 1991 through 1992 during high aquifer-level conditions, the cave was reenacted as an active flow system, discharging about two cubic feet per second to Barton Creek.

Localization of Sediment and Trace Metals Along the Sunset Valley Flow Route

During the course of a four-year water quality study, the Barton Springs/Edwards Aquifer District documented anomalous occurrences of sediment in the aquifer as well as some of the consequences of sediment contamination. A methodology was developed to assess the occurrence and accumulation of sediment in the aquifer. The degree of



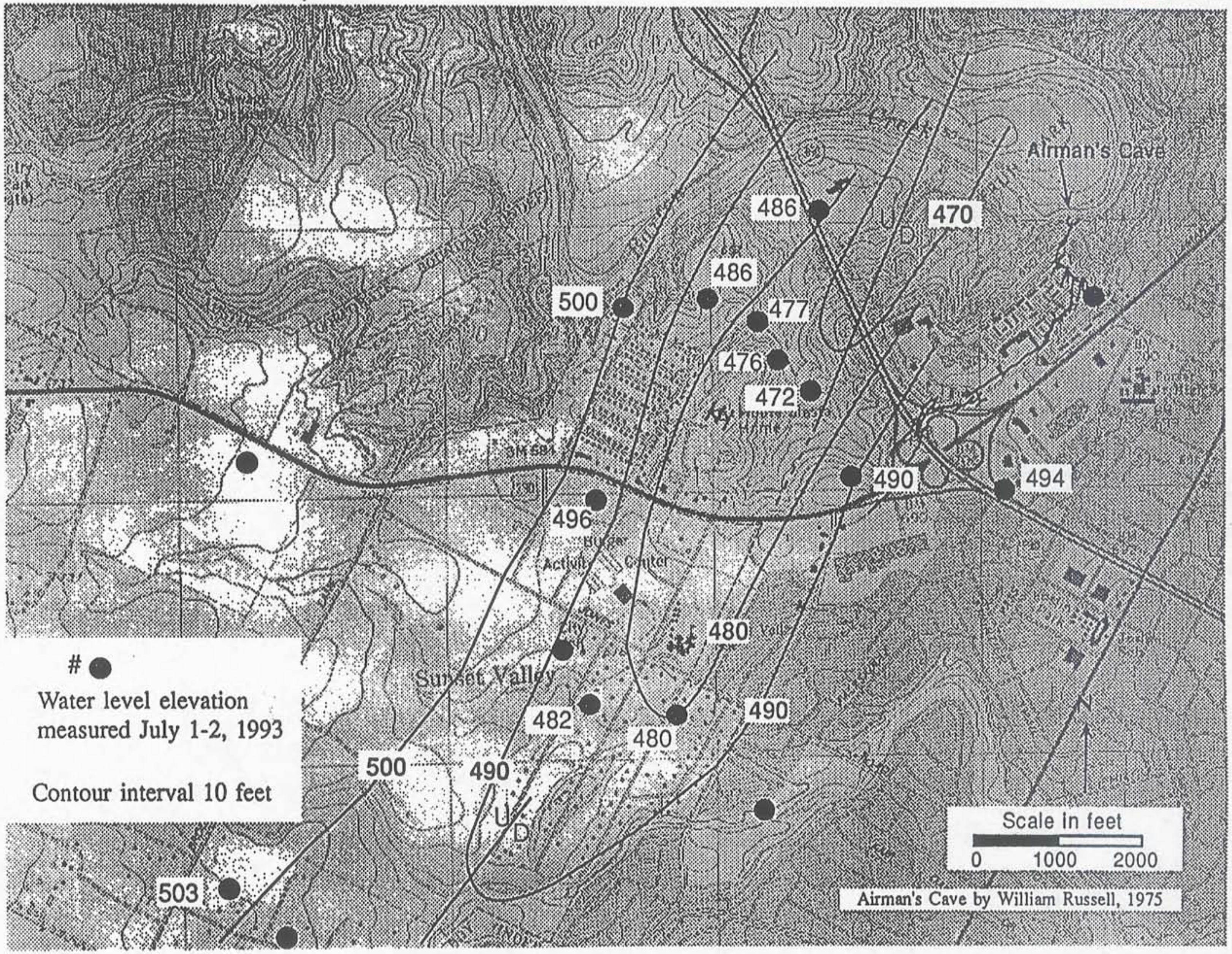
Airman's Cave by William Russell, 1975

Wells Used for Hydrogeologic Data in the Southwest Austin and Sunset Valley Areas

Barton Springs/Edwards Aquifer Water Quality Study

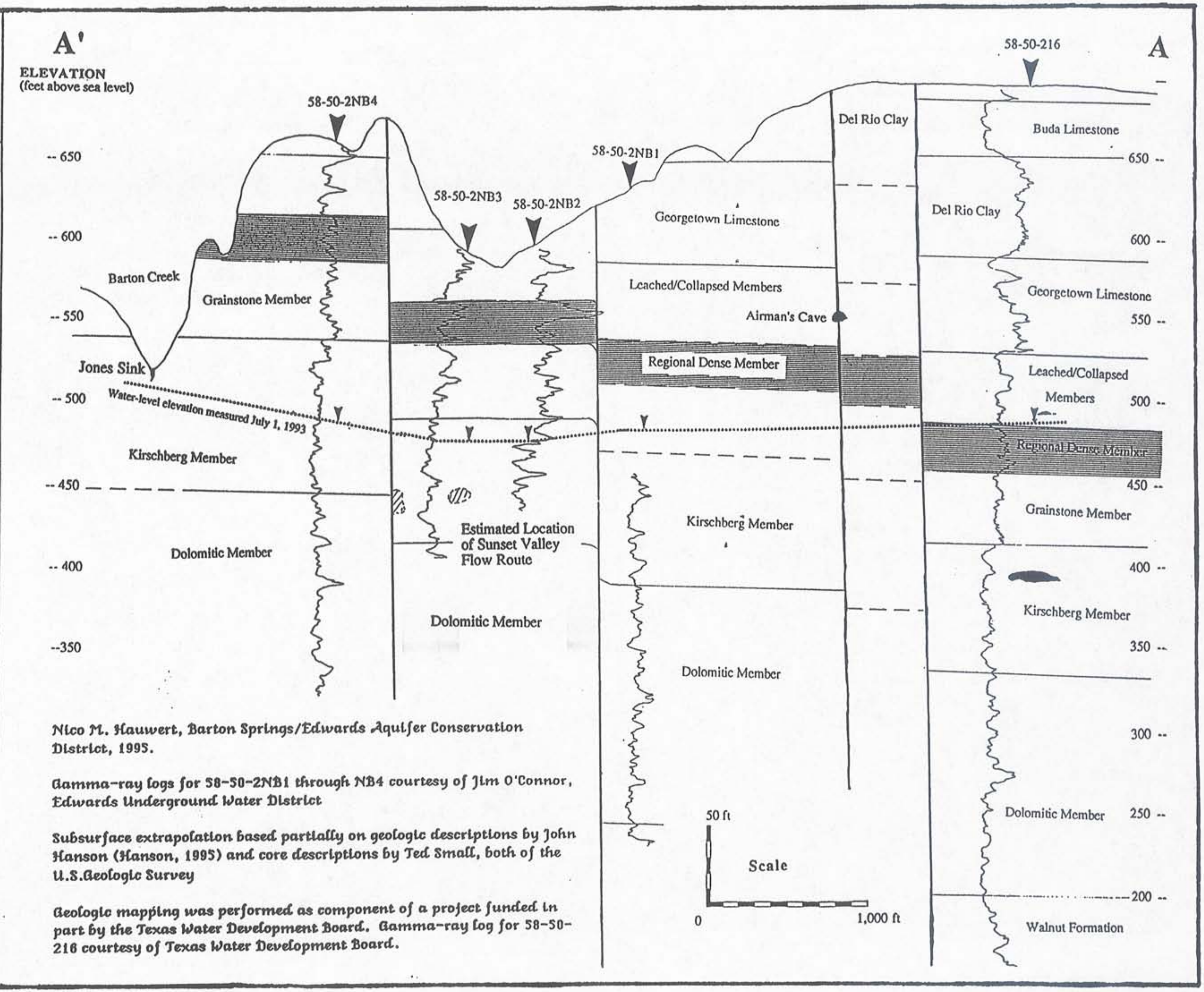
Figure 2

Potentiometric Map of the Southwest Austin and Sunset Valley Areas (July 1-2, 1993)



Barton Springs/Edwards Aquifer Water Quality Study

Figure 3



HYDROGEOLOGIC CROSS SECTION
ALONG LOOP 360, WEST OF HIGHWAY 290,
SOUTHWEST AUSTIN, TEXAS

Barton Springs/Edwards Aquifer
Geological Mapping Study

Figure 4

sedimentation in the aquifer was gauged using:

a) reports of encounters with sediment by drillers, well operators, owners, and service persons, USGS staff, and the Barton Spring pool manager.

b) field measurement of turbidity using an Horiba U-10.

c) laboratory measurement of total suspended solids.

d) measurement in the changes in the depth of a well over time.

As one would expect, the sediment contamination appeared to be limited to the recharge zone where overlying protective clays are absent. Based on reports of sediment accumulations and samples from more than 40 observation wells and springs across the Barton Springs Segment, it was apparent that anomalous levels of sediment were localized in the Sunset Valley and Barton Creek area along the suspected Sunset Valley flow route to Barton Springs (Figure 5).

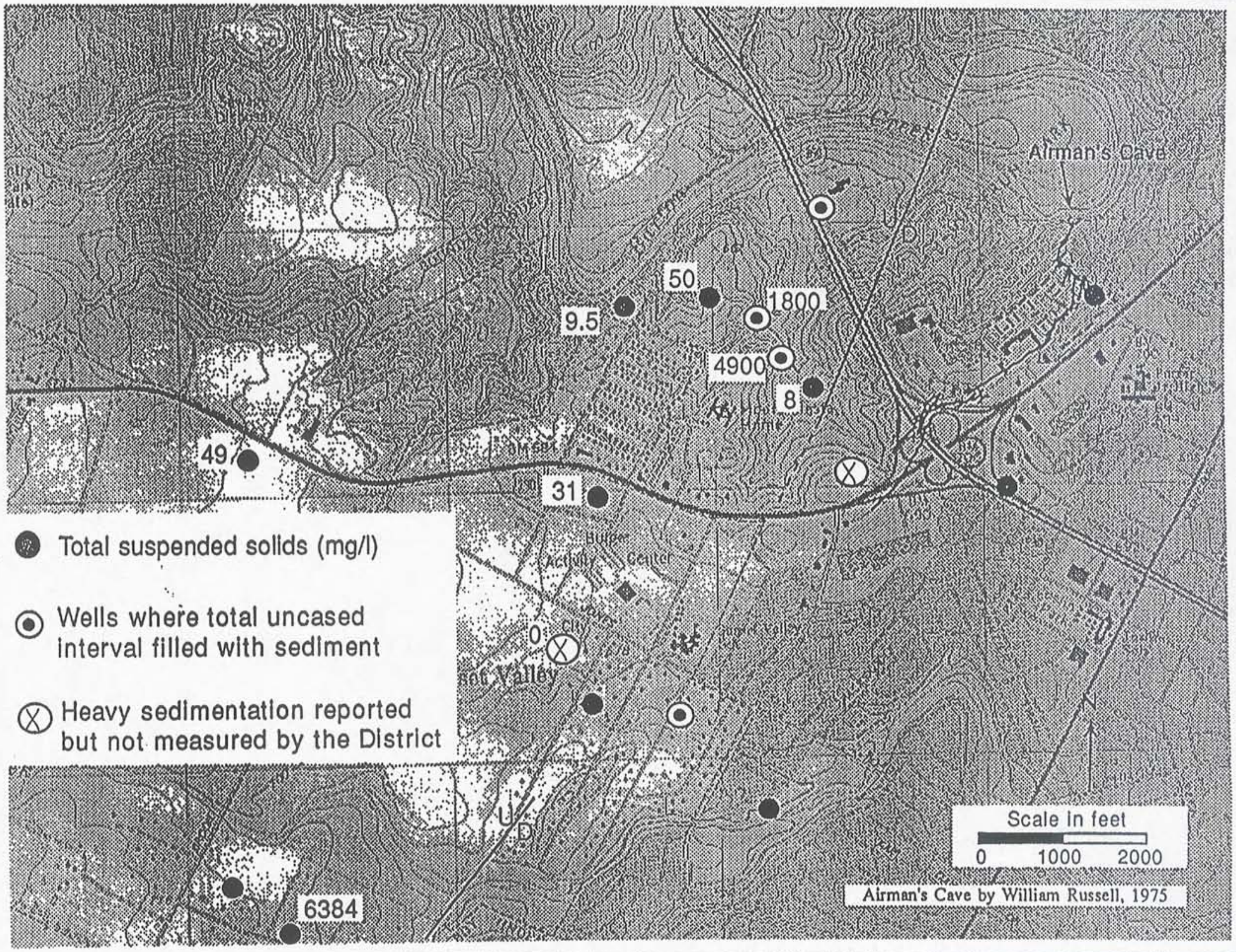
Because of its karstic nature, the Barton Springs Edwards Aquifer allows accumulation and transport of sediment, unlike diffuse-flow aquifers. Note that for sediment transport in an aquifer requires:

1) minimal cavity size (conduit flow) from source area to deposition area.

2) sufficient groundwater velocity from source area to deposition area.

3) source area producing significant volumes of sediment. The identification of specific source areas were out of scope of this study. However we can examine some potential sources:

    a) terra rosa-weathered soils and dissolution of original rock leaving recrystallized mineral enriched in trace minerals deposited in caves. The characteristic red color may be resulting from enrichment of less soluble minerals such as iron. The sediment recovered from wells in the area have generally been creme-colored, rather than red, however. The volume of naturally-produced sediment by this means can be expected to be limited.



Sediment Accumulations in Wells of the Southwest Austin and Sunset Valley Areas

Barton Springs/Edwards Aquifer Water Quality Study

Figure 5

b) fine-grained gouge caused by grinding action along faults. The volume of sediment produced along fault surfaces can be expected to be limited and therefore is not a likely source for the sediment observed in the Sunset Valley area.

c) Sediment from recent ground disturbance. This source is the most likely based on creme-colored appearance of sediment found in wells and springs, and the timing of sediment observations in aquifer with periods of local construction.

The timing of sediment observations coincides with periods of times of heavy construction in the area in early 1980's and early 1990's. Turbidity has been observed since the early 1980's in Barton Springs pool immediately following major rain events. Sediment flows from the aquifer into Barton Springs pool dramatically increased during the early 1990's in both occurrence and duration. Higher in the recharge zone of the Barton Springs Segment, the well bores of wells 58-50-2NB2, 58-50-2NB3, 58-50-221, 58-50-222, and USGS monitor well 58-50-217 have each been filled with 70 to over 150 feet of sediment.

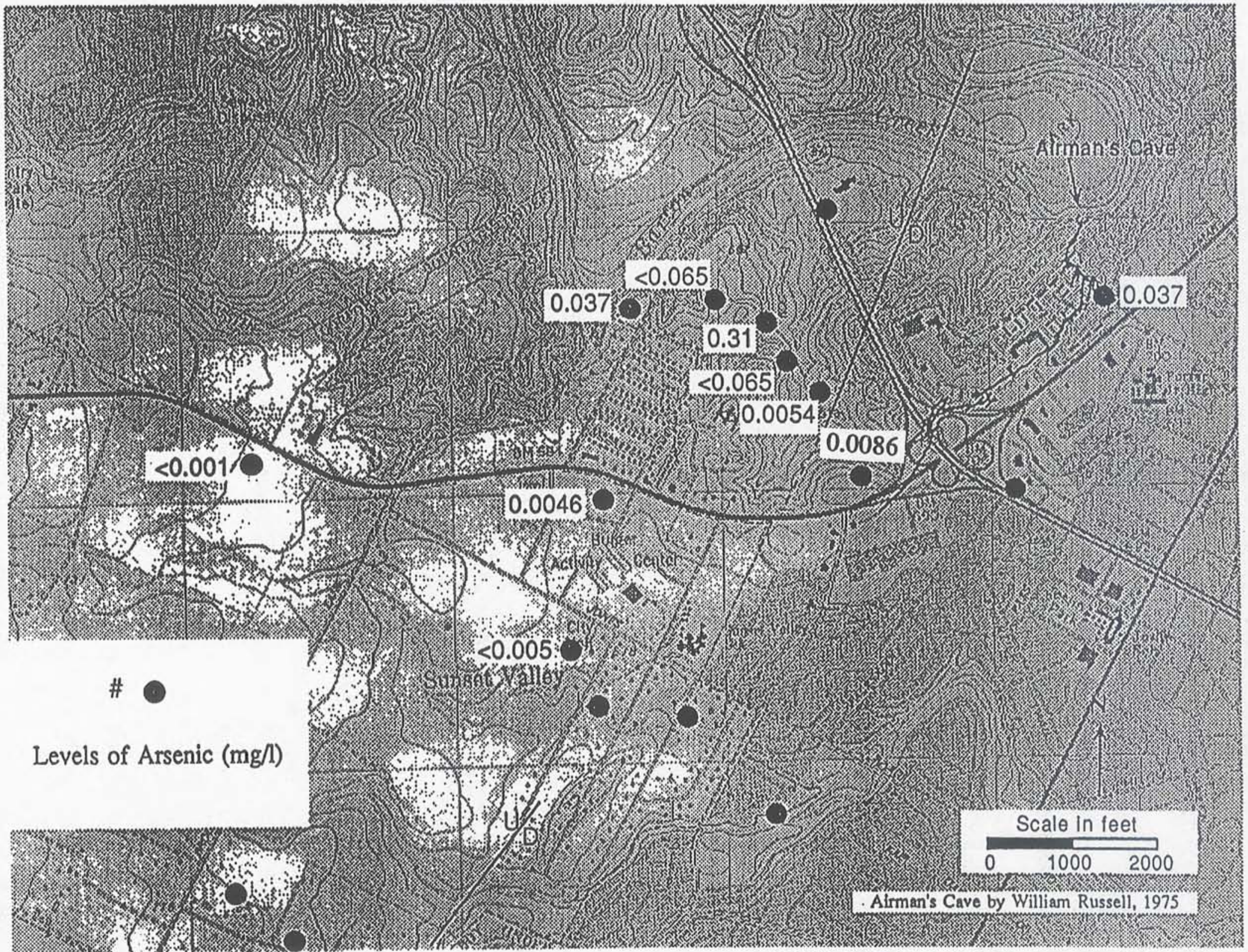
A municipal well in Sunset Valley, 58-50-223, began accumulating sediment in each of its two 44,000 gallon water-storage tanks in 1990. This accumulation greatly increased in 1993, when 1 to 1.5 ft of sediment were encountered in two storage tanks from January to July, 1993. In July 1993 the well pump seized. During this time significant increase in deposition of sediment could be observed in Austin area creeks and discharging from Barton Springs pool. Microscopic and minerologic analysis of some of the sediment samples is being conducted by the University of Texas to further characterize the source.

There are local sources that could account for the anomalous sediment observed along the Sunset Valley flow route. Large amounts of urban runoff have been directed to recharging creeks upgradient of the southwest Austin study area, particularly Gaines Creek which parallels Highway 290. A turbidity survey conducted by City of Austin staff along Gaines Creek showed levels of suspended solids of about a thousand milligrams per liter (mg/l) entering Gaines Creek below Mopac Boulevard, compared to three mg/l flowing along Barton Creek, upstream of Gaines Creek (Johns, 1991). A sinkhole on Barton

Creek below Mopac, and other nearby recharge features appears capable of recharging about 10 cubic feet per second during moderate flow conditions, based on USGS creek surveys (Baker, and others, 1986) and unpublished flow measurements taken by DGR and Associates and BS/EACD staff in 1995. After rain events during low aquifer-flow conditions, the entire flow of Gaines Creek that reaches Barton Creek can be observed to flow in the upstream direction of Barton Creek into sink near Mopac. This sink may be a "window" for local sediment to enter the subsurface near the Sunset Valley flow route. Similar recharge points have been observed on Williamson Creek near the extension of the Sunset Valley flow route that could account for some of the sediment encountered in Sunset Valley.

As part of the aquifer-wide water-quality sampling, the parameters of total and dissolved trace metals were tested. Arsenic was measured consistently below detection limit (<0.001 mg/l) in rural areas, but could be measured in surface and groundwaters adjacent to urban areas. Some of the higher levels of arsenic were localized near the Sunset Valley flow route (Figure 6). Previous studies have associated elevated levels of arsenic with urban and roadway runoff (Veenhuis and Slade, 1990; Wanielista, and others, 1980). The water-quality results presented here are generally based on a single sample from each well or spring. Additional sampling is needed to measure the variation in dissolved and total metal concentrations over the duration of rain events and different seasons.

What steps can be taken to reduce sediment and trace metal loads to the aquifer? The amount of construction activity in this area can be expected to increase over the next few years. Based on our current and forseeable technology, it does not appear possible to build over a karst aquifer without impacting the groundwater quality. The amount of construction activity is based on choices of individuals to live on and utilize facilities over the recharge zone. Diligent maintenance of temporary controls and water-quality ponds on construction sites can reduce the amount of sediment leaving construction sites and potentially recharging into the aquifer. Releases of sediment from construction sites should be reported to the contractor and the TNRCC Region 11 Field Office (463-7803). Currently, the Texas Department of Transportation (TxDOT) is constructing a number of filtration ponds near Loop 360 and Barton Creek and three major outfalls along Highway 290 and Gaines Creek. Once installed, these ponds will require monitoring, maintenance, and possibly some degree of modification by TxDOT to be effective in filtering not only sediment but other components of urban runoff.



Distribution of Arsenic in Wells of the Southwest Austin and Sunset Valley Areas from Single Measurements Taken 1993 through 1995

Barton Springs/Edwards Aquifer Water Quality Study

Figure 6

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BALCONES FAULT ZONE AND COLORADO RIVER-- DUAL CONTROLS ON THE EDWARDS AQUIFER NEAR AUSTIN, TEXAS[1]

C.M. Woodruff, Jr.

"The really fundamental geological elements of Austin are two: the (Colorado) river with its valley and the Balcones fault system."

Peter T. Flawn

LOCAL CONDITIONS

With an outstanding economy of words, a single sentence has been employed by Flawn (1990 p. 228) to characterize the key geologic attributes of Austin, Texas. An examination of the subunits of the Edwards Aquifer in the Austin area emphasizes the truth of this statement, as the structural geometry, physiographic setting, and groundwater regimes are dramatically different across the main fault line and on the two sides of the Colorado River. A geologic map of the Austin area (fig. 1) clearly documents the abrupt changes in outcrop geometry of the Edwards Limestone north and south of the Colorado River and east and west of the Mount Bonnell Fault (Garner and Young, 1976). North of the Colorado River, the most areally extensive outcrop of Edwards Limestone lies immediately west of the main fault line. There, this resistant limestone unit caps the Jollyville Plateau and forms a disjunct eastern outlier of the once more continuous Edwards Plateau. This plateau outlier is held up by less than 100 ft of the basal Edwards Limestone. South of the Colorado River, in contrast, the contiguous outcrop of Edwards Limestone occurs east of the Mount Bonnell Fault. There, virtually a complete section of Edwards Limestone is downfaulted against the Glen Rose Limestone on the west side of the fault line. Edwards exposures west of the fault line are limited to isolated hilltops and local ridges, and consist of the bottom twenty ft or so of the 350-ft-thick Edwards section.

North of the Colorado River, beneath the Jollyville Plateau, groundwater occurs in shallow and locally discontinuous horizons under water table conditions. Discharge of groundwater occurs in a distributive manner. That is, water flows out the edges of the relict table land, with spring flow occurring most abundantly where streams breach the edges of the dissected plateau. Elsewhere, ephemeral seeps discharge during wet periods. For much of the Jollyville Plateau terrain, the aquifer host rock is thin, consisting only of the basal few tens or scores of feet, and volumes of water stored and transmitted are perforce limited. Wells drawing on this shallow aquifer are few and are typically shallow and are capable of only low yields. Little concentration of surface flow results in diffuse recharge with the bulk of incident rainfall being cycled back to the atmosphere through the processes of evapotranspiration. Although the limestone host rock progressively thins to the north, in areas east of the main fault line, the Edwards Aquifer becomes thicker than that seen along the edges of the Jollyville Plateau. Given a greater saturated thickness and several streams providing loci of concentrated recharge, the aquifer is a more prolific water producer farther north providing potable supplies for the towns of Pflugerville, Round Rock, and Georgetown and numerous farms and ranges in the area. Locally important springs occur along the main fault line from Georgetown north to Salado and beyond (Yelderman, 1987).

[1] Originally published *in*: Johns, David A. and C.M. Woodruff, Jr., 1994, Edwards Aquifer -- water quality and land development in the Austin Area, Texas: Field Trip Guidebook, Gulf Coast Association of Geological Societies, 44th Annual Convention, p. 1-9.

Explanation:
Ked-JP -- Edwards Limestone underlying the Jollyville Plateau
Ked-BSS -- Edwards Limestone underlying the Barton Springs Segment

Figure 1. Simplified geologic map of the Austin area showing Edwards Limestone outcrop areas north and south of Colorado River and east and west of the Mount Bonnell Fault (modified from Garner and Young, 1976).

South of the Colorado River, and west of the Mount Bonnell Fault, the entire Edwards section has been removed by erosion across most of this area. There, the "stair-step hills" typical of the Central Texas Hill Country is underlain chiefly by Glen Rose Limestone, and this landscape composes the contributing zone upstream from the main recharge areas of the Barton Springs segment of the aquifer. In this contributing area, little or no hydrologic communication of groundwater occurs across the main fault line. Instead, stream flow is channeled to the six major creeks that drain the contributing landscape and convey surface water across the main fault line. There, on the recharge zone, approximately 85 percent of total recharge to the Barton Creek segment of the aquifer occurs within the channels of Onion, Barton, Slaughter, Bear, Little Bear, and Williamson Creeks (Slade and others, 1976). Recharge occurs into the thick, nearly continuous section of karstic limestone, and as the groundwater moves downdip to the east, it becomes confined beneath overlying low-permeability strata and moves under artesian pressure to the northeast to Barton Springs, which is virtually the only natural discharge point for this segment of the aquifer. Thus, in contrast to the distributive, shallow, low-yield aquifer seen on the Jollyville Plateau, the Barton Springs segment of the aquifer is a prolific integrated system channeled to a single natural discharge point.

Explained in context of Flawn's two major geologic controls, the Balcones Fault Zone juxtaposes the entire thickness of the Edwards Limestone against less permeable strata on both the west and the east. Faults and associated fractures also provide initial conduits for groundwater flow, and many of these porous zones became enlarged by dissolution with ongoing positive-feedback as discussed by Abbott (1975), such that initial concentration of groundwater flow enlarged conduits, allowing more water to flow within these conduits, which in turn, resulted in yet further localized dissolution. Overall southwest-to-northeast groundwater flow within the artesian zone moves along the general trend of major faults of the Balcones fault system. The primary natural discharge point, Barton Springs, is situated where it is because of the base level provided by the Colorado River. The artesian flow drains to this topographic low point just as do surface streams.

REGIONAL CONTEXT/REGIONAL CONTROLS

Viewed in a regional context, the subsections of the Edwards Aquifer noted north and south of the Colorado in the Austin area are merely two subset hydrologic segments of a vast karst limestone system--that collectively make up the many disjunct parts of the Edwards Aquifer (fig. 2). Each subset is denoted by a catchment area in which recharge is received and transmitted to one or more natural discharge points. The most prolific segment occurs along the Balcones Escarpment from Hays County west to Kinney County and supplies water for the City of San Antonio, the largest city in the United States to be supplied solely by groundwater (although recent court challenges suggest that San Antonio may have to augment its use of groundwater with some surface supplies [McKinney, D.C., and Watkins, 1993]). This main (San Antonio) segment is larger and more complex, but in general, it functions similar to the Barton Springs segment: The Balcones Fault Zone localizes the aquifer recharge zone, provides a general southwest-to-northeast porosity and aquifer boundary system along faults, and spring sites are localized at topographically low points along major streams where they cross the Balcones Escarpment (Woodruff and Abbott, 1979, 1986). Similar controls are provided by Balcones faulting and the modern drainage network for the Del Rio/San Felipe Springs segment, which lies along the western part of the Balcones Fault Zone (the aquifer extends into Mexico, but it is not well documented beyond the Rio Grande). Likewise, similar controls occur north of the Barton Springs segment within the northern Balcones segment, which extends from the Colorado River north to the Salado vicinity (although an outlier of the Edwards Plateau, the Jollyville Plateau is considered a sub-segment of a more-inclusive

"Northern Edwards Aquifer"). Farther north still, in extensive areas of north-central Texas, studies by Yelderman (1987) document yet other areas in which groundwater is obtained from the Edwards Limestone and hydrologically associated members of the Georgetown Limestone within the Washita Prairie physiographic region. North and west of the main water-yielding segments along the Balcones Escarpment is the vast Edwards Plateau, which is in hydrologic communication with the underlying Trinity Group aquifer, and thus is considered by Texas water agencies as the "Edwards-Trinity aquifer" (Texas Water Development Board, 1991). This unconfined aquifer system is controlled by the topography of the Edwards Plateau, whose margin is sculpted by streams cutting into the plateau edges.

As stated at the outset, the two major controlling factors on the geology (hence, on groundwater) in the Austin area are the Balcones fault system and the Colorado River. The dual influences of Balcones fault geometry, and surface drainage evolution on recharge/discharge geometry has been noted by Woodruff and Abbott (1979) within the San Antonio segment of the Edwards Aquifer; similar controls have been noted for the Barton Springs segment, as well (Woodruff, 1984; Woodruff and Abbott, 1986). Stream piracy along the Balcones Escarpment diverted major streams, thereby providing concentrated surface flow, which resulted in deep valley incision within the downfaulted Edwards Limestone. This incision also provided the topographically low points that acted as "drains" for pent-up groundwater; in this way, major spring sites were established where streams cross major faults.

Drainage-basin evolution has also affected the hydrologic attributes of the Jollyville Plateau and of the contiguous Edwards Plateau. The implications of the Jollyville Plateau as an outlying remnant of the Edwards Plateau have been presented by Woodruff (1985, 1987, 1990). A brief review of regional drainage evolution as it has influenced the plateau uplands of Central Texas is presented here.

In the vicinity of the Balcones Escarpment, the Colorado River system appears to be enlarging its drainage basin at the expense of the Brazos watershed. There, the Colorado River exhibits a constricted watershed, and the main stem of the river lies as little as 5.5 straight-line miles from the Brazos/Colorado divide at the margin of the Bull Creek basin. The upper reaches of Bull Creek were once almost certainly part of the Brazos watershed, but the creek was captured by high-gradient streams flowing to the nearby base level provided by the Colorado River. In contrast, the main trunk stream of the Brazos River crosses the Balcones Fault Zone approximately 100 straight-line miles to the north, so that streams within this part of the Brazos watershed typically exhibit low stream gradients. Thus, given its location along a major divide, the Jollyville Plateau is maintained as an upland remnant and an unconfined shallow karst aquifer. With much of its bedrock section draining to springs around the edge of the Bull Creek watershed, this outlying water-table aquifer segment has been drained of most of its saturated thickness, and as a result, vadose-zone caves are abundant and extensive. Because of these widespread caves, the Jollyville plateau contains prime habitat for air-breathing troglobytic arthropods, 5 of which are currently listed as Endangered Species by the U.S. Fish and Wildlife Survey (U.S. Government Printing Office, 1988).

In a broader (state-wide) context, all but one of the main tributaries of Colorado River west of the Balcones Escarpment flow from west to east, thereby entering the river from the south (fig. 3). Thus, the Concho River system, as well as the San Saba, Llano, and Pedernales Rivers, all drain the southwestern part of the upper Colorado River basin. The headwaters of these streams are all fed by the Edwards-Trinity aquifer from the margins of the Edwards Plateau: erosion by these headwaters (as well as subsurface sapping of the plateau by groundwater) mark the edge of the physiographic plateau. The overall geometry of drainage

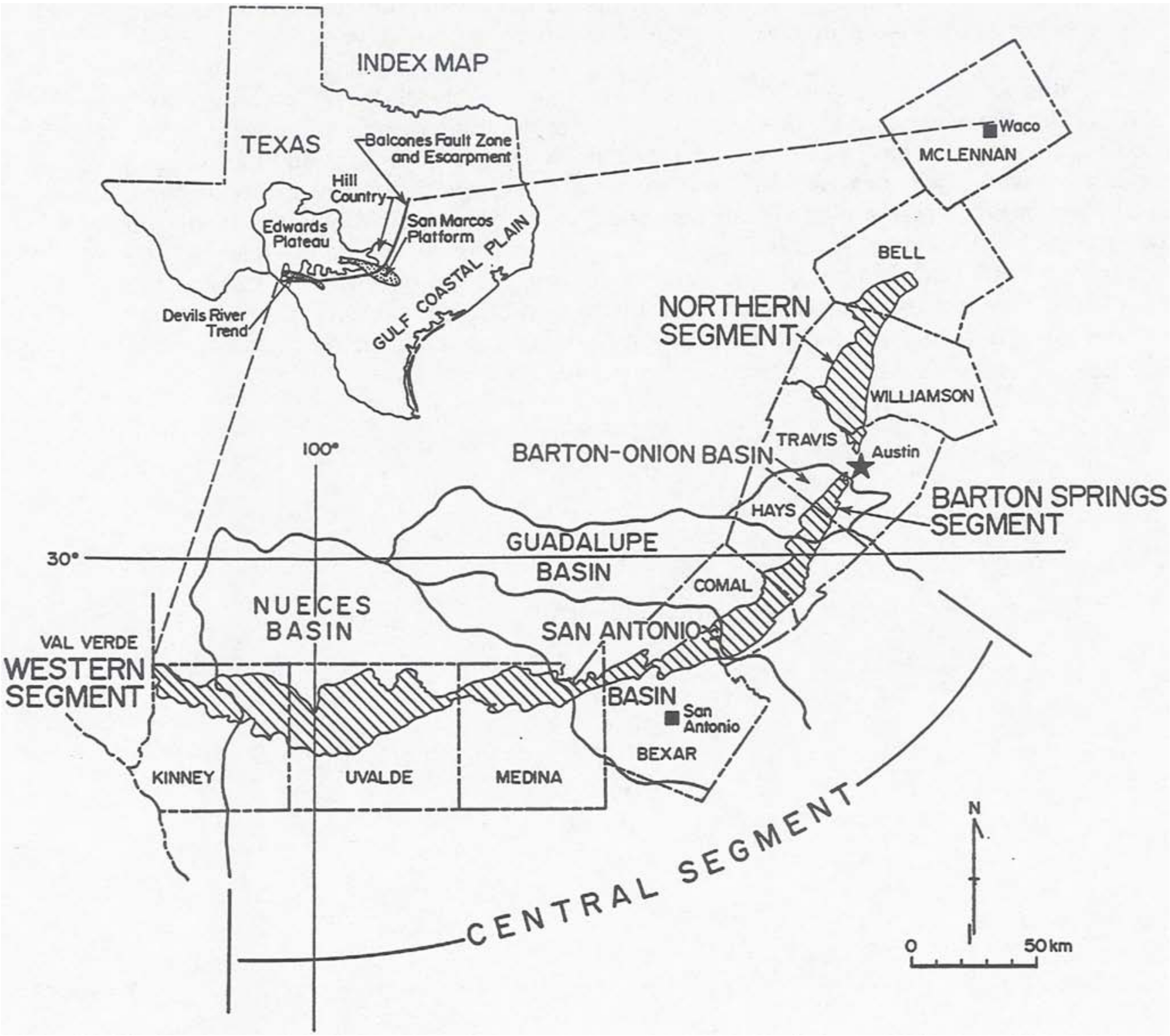
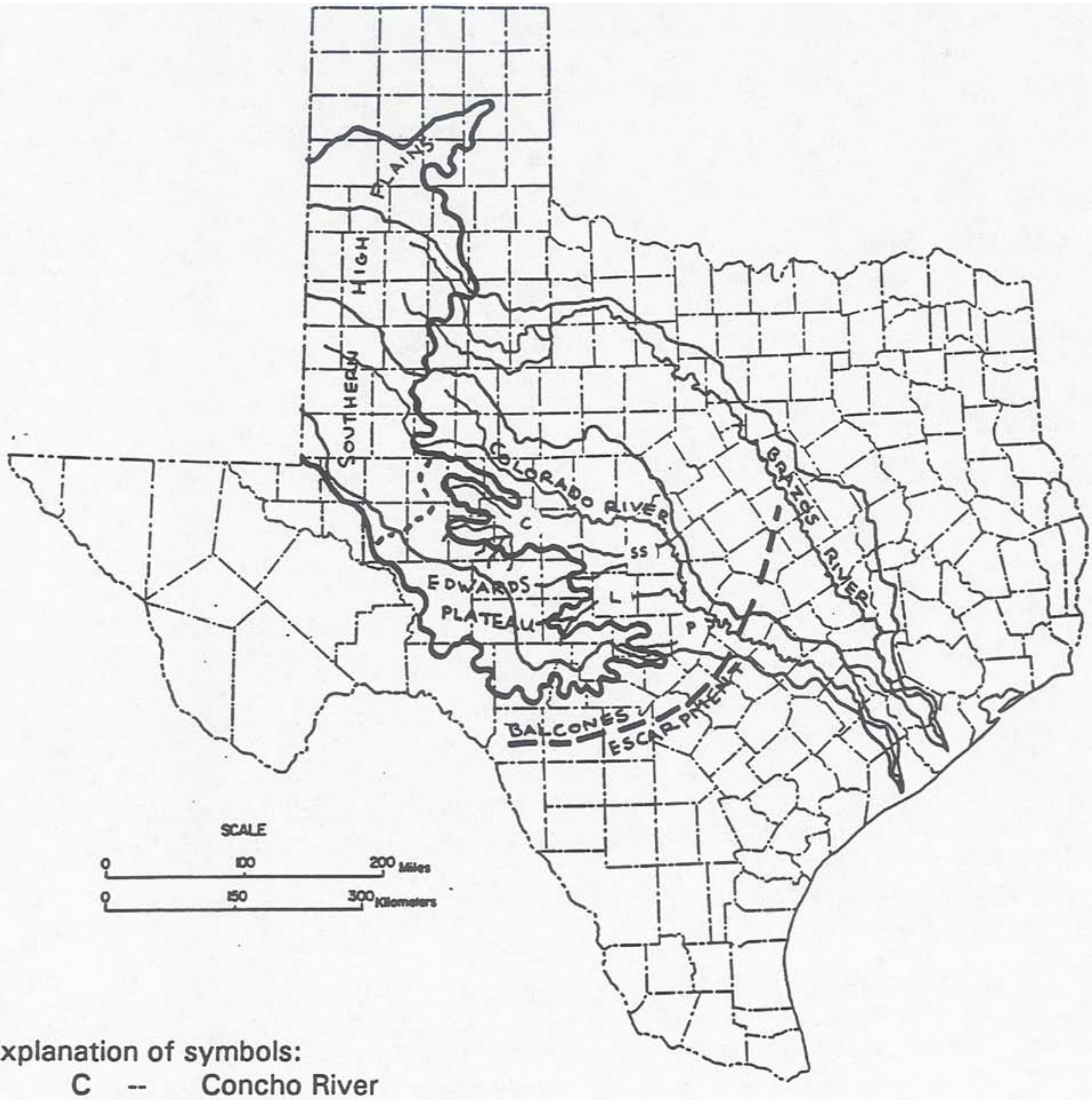


Figure 2. Region-wide map showing major groundwater-bearing segments of the Edwards Limestone (from Woodruff and Abbott, 1986).

nets west of the Balcones Escarpment suggests that, over the long term, the Colorado River is expanding its watershed at the expense of the southern part of the Brazos watershed. Thus, the Jollyville Plateau is not only a relict upland, but in the long-term of geologic time, it is being dissected relatively quickly, owing to the progressive encroachment of the Colorado watershed at the expense of the Brazos. The occurrence of the Jollyville Plateau as a relict upland is a local example of long-term regional landscape evolution, which involves possible structural control of drainage-basin evolution, dissection of a resistant limestone caprock, and chemical sapping of plateau uplands through dissolution by groundwater.

In summary, the Jollyville Plateau is being aggressively dissected on its southern edge, and it is likely being sapped by groundwater dissolution from within, and in fact, there is evidence for ongoing stream piracy via underground diversions of water within karst features connecting Buttercup Creek (within the Brazos watershed) with the Bull Creek system (Russell, 1993). Similar processes are occurring elsewhere along the Brazos/Colorado divide--Post Oak Ridge north of Lake Travis, for example. In this way, aquifer attributes are less important for sustaining human demands for groundwater, but are more important for sustaining localized ecological niches--for example, maintaining inputs of moisture and nutrients to the vadose-zone cave habitats, and the mesic seep/spring habitats at the dissected margins of these outlying tablelands.



Explanation of symbols:

C -- Concho River
SS -- San Saba River
L -- Llano River
P -- Pedernales River

Figure 3. Statewide view of generalized Colorado River drainage network and major tributaries showing west-to-east extension of sub-basin network compared to Brazos watershed and main stem of the Brazos.

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REMOTE SENSING AND NEOTECTONIC ANALYSES OF POSSIBLE GROUNDWATER FLOW PATHS IN KARST

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ABSTRACT

Morphometric neotectonic analysis of relief energy and remote sensing of lineaments were applied to the drainage area of Barton Springs in the Edwards Aquifer, Texas. The method of relief energy was implemented using an in house application, while Spyglass Transform and Image software packages were used for the processing of USGS digital terrain models (DEM) of 7.5 minute topographic base maps. In addition to the geologically well known and previously mapped faults of the SW-NE strike (the NW I Balcones Fault Zone), the analysis uncovered probable neotectonically active zones with SE- strike, i.e. perpendicular to the Balcones Faults. Lineament analysis performed on the Landsat MSS images confirmed the presence of both systems, as well as of one with a SSE-NNW strike. Landsat images were digitally processed, enhanced and filtered using Adobe Photoshop. Neotectonically active zones are a primary candidate for the preferential groundwater flow paths in karst aquifers. In addition, definition of relatively down thrown tectonic blocks provides a foundation for the delineation of local erosion bases within lithologic units; lower blocks are assumed to be subreservoirs collecting groundwater from the higher blocks.

INTRODUCTION

The Edwards Aquifer of central Texas is among the most famous of karst aquifers in the United States, both for its abundant groundwater, and for the environmental and legal problems associated with groundwater exploitation. The lack of an accepted management plan for the Edwards Aquifer, a steady increase in regional groundwater pumpage, and a lawsuit by the Sierra Club against several federal agencies, have led to the introduction of the Edwards Aquifer bill. The bill includes provisions that will protect endangered species, facilitate the gathering of data on water use, adjudicate water rights, encourage limited water marketing and promote the development of surface water in the San Antonio area (TWRI, 1993). However, the intense usage of the aquifer's resources has not been followed by proper research efforts towards their quantification. Karst aquifers are well-known for their unique within-rock void distribution: one can find porosity of homogeneous rock blocks (matrix porosity), porosity of small-to- large fissures, porosity of large dissolutional cavities (karst caverns, channels and tubes) and, finally, porosity of clastic deposits in all the above mentioned discontinuities. This mixed porosity of karst aquifers makes quantification of exploitable groundwater reserves, as well as the prediction of pollution transport, more difficult as compared to other porous media. Groundwater modeling approaches that simulate karst aquifers as homogeneous porous continua are not hydrodynamically justified. A good example is the groundwater flow model of Barton Springs drainage area by Slade et al. (1985). Heterogeneity of karst aquifers, and almost always existing preferential flow paths, should be incorporated in every modeling effort.

Hydrogeologic investigations of the Edwards Aquifer in the Austin region suggest tectonic control of preferential groundwater flow paths (Senger and Kreitler, 1984, Senger et Al., 1990). This control is attributed to a system of large faults, known as the Balcones Fault Zone, with a southwest-northeast orientation. The system is shown on the Geologic Map of the Austin Area, scale 1:62,500 (Garner et al., 1976) and the Austin Sheet geological map, scale 1:250,000, of the Geologic Atlas of Texas (Proctor et at., 1981). However, none of the works suggests the presence of other major fault systems in the area or addresses the possible neotectonic control of intermittent surface streams that cross the Balcones Fault Zone.

MORPHOMETRIC NEOTECTONIC ANALYSIS

The analysis of neotectonic activity, i.e. recent tectonic movements, plays an important role in delineating zones of rock mass that are disintegrating due to faulting and fissuring. In the case of karst aquifers this also means delineation of the zones of higher porosity and developed as a result of the enhanced dissolution of mechanically weakened rock. These zones are thus a primary candidate for groundwater flow which is often difficult to define in karst aquifers. In addition, definition of relatively down thrown geologic blocks provides a foundation for the delineation of local erosion bases within lithological units: lower blocks are assumed to be sub reservoirs collecting overflowing groundwater from the higher blocks. This is also the concept of so-called *cell models* of ground water flow in karst terranes (Kresic, 1991). Definition of preferential groundwater flow paths and subreservoires should be essential for the design of numerical models of karst aquifers.

Relief Energy

Relief energy is defined as the potential energy, of the earth's surface at a given point (E=MGH). At this point the relief represents a spatial position of a rock mass which has its potential energy. If the surface area under consideration is small enough ("unit area"), the rock mass within it may be assumed to have constant value. The gravity acceleration within the unit area may also be considered as constant. Therefore the relief energy within the unit area is defined only by its height or, more precisely, by the height difference between the highest and lowest points.

On a local scale the relief energy is influenced by the lithology and action of exogenous geomorphologic factors, mainly surface ("running") water. Systematic measurements and statistical 290 analysis of the relief energy may locate areas of its highest and lowest values, i.e. areas of increased erosion and areas of increased deposition respectively.

On a regional scale increased erosion and deposition reflect the presence of recent tectonic activity Regional analysis of relief energy may indicate the position of neotectonic structures and vertical direction and relative intensity of movements, thus providing important information for various earth-related studies (Markovic, 1983; Kresic and Tasic, 1984).

The base for the morphometric analysis of relief energy in the Barton Springs area was a digital elevation model created by merging nine USGS DEM 7.5 minute quadrangles. The original data, with 3- second resolution, were converted to the UTM coordinate system with MacGridzo and resampled to a 5Ox5O m grid using Spyglass Transform (Figure 1). An in-house application, REN, was then used for the calculations of relief energy and its first two trends with the following procedure:

1) Determine elevation difference between the highest and the lowest relief point within a 5OOx5OO m unit area which consists of 100 data points. Assuming that the rock mass is constant, the obtained value corresponds to the potential energy of the relief surface represented by the unit area;
2) Determine the reference surface for the study area by averaging all relief energy points; Subtract individual values of the relief energy from the reference surface. Positive values represent areas that are relatively uplifting, while negative values represent down

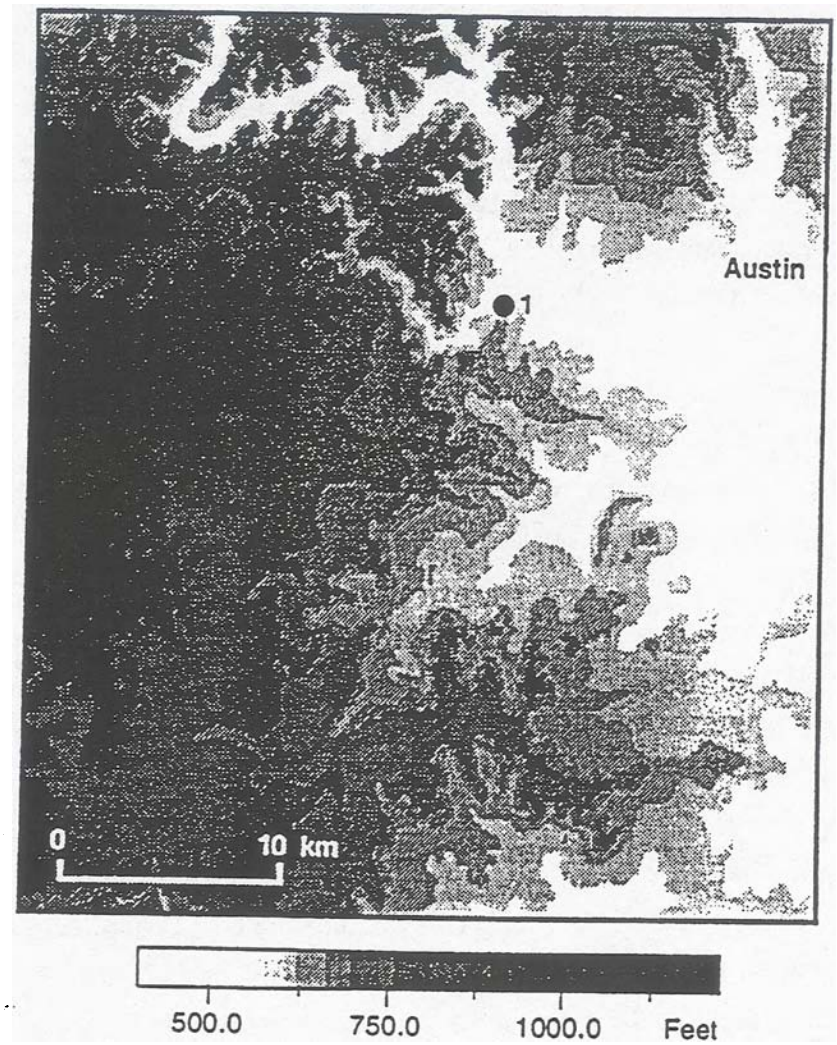


Figure 1. Digital elevation model of the study area (1-Barton Springs).

dropping;

3) Find first and second trends of the new (relative) relief energy surface, applying a simple one-pass linear digital filter in Spyglass Transform. The procedure removes the influence of local active exogenous processes ("noise") on the relief and enhances the results of recent regional endogenous (tectonic) movements-uplifting and down dropping.

Figure 2 shows the second trend of relief energy for the study area (vertical scale is in feet). Figures A through D are the result of a gradually decreasing contrasting of the digital domains using Image. Image is a public-domain software package developed at the National Institute of Health. Although initially designed for the analyses of microphotographs, it has been successfully used for various qualitative and quantitative analyses of remote sensing digital images (Morgan an et al., 1992). The contrasting, process with Image allows a fine analysis of the relief energy differences that may be less obvious on the Spyglass Transform images. It is practically irreplaceable when the analysis is performed using the gray scale only (or black-and-white monitors) since neotectonically active zones with the highest initial contrasts may be less distinct or even "lost" as the contrasting decreases. Two such zones are shown on figures 2A and 2B for the illustration. Dark/black areas in Figures 2 are neotectonic blocks that are relatively uplifting. The most distinct block is in the northwest and contains incised meanders of the Colorado River. It should be noted that the highest relief in the study area is in its western part (see Figure 1) and that it does not coincide with the highest relief energy.

The narrow zones between the uplifting blocks and the down dropping blocks (light/white areas) are neotectonically active. They may represent large individual faults or systems of close parallel faults with the predominant vertical component. Figure 2D shows neotectonically active zones as black/white lines between the neotectonic blocks.

The method of relief energy, as well as other quantitative geomorphologic analyses commonly used in neotectonic studies, is weighted by the interpreter's subjectivism because of its statistical nature and the impact of exogenous agents on the relief evolution (Markovic, 1983). Therefore any morphometric neotectonic analysis should be accompanied by at least geologic and remote sensing studies. Figure 3 shows a comparison of the probable neotectonic zones in the Barton Springs area and the faults shown on the published geologic maps (Garner et al., 1976; Proctor et al., 198 1). The two most distinct systems of the neotectonic zones are with SE-NW and SW-NE orientations, while practically only the faults with SW-NE strike (Balcones system) are

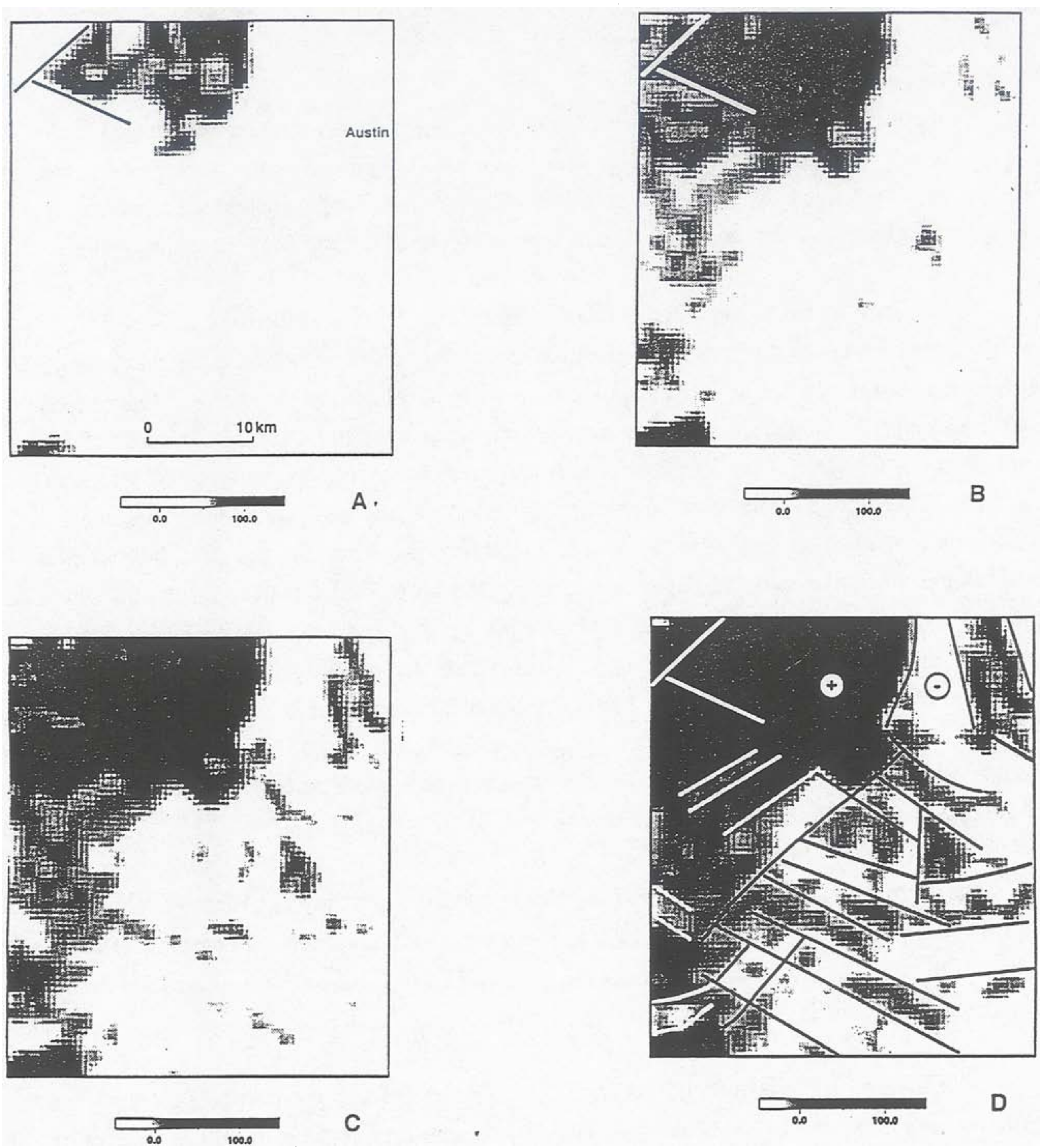
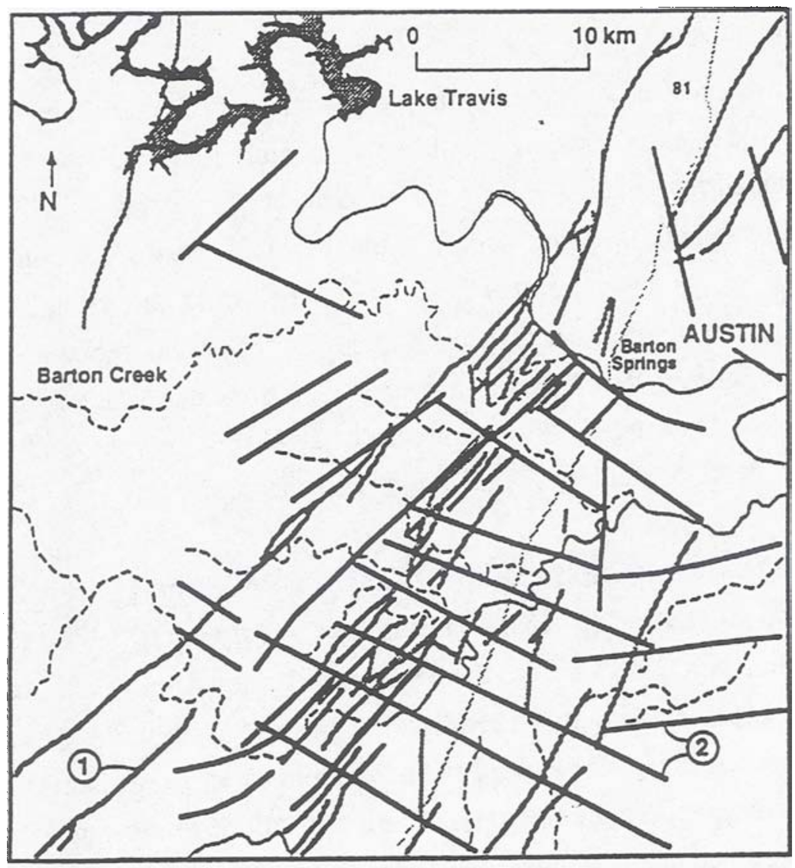


Figure 2. Map of the second trend of the relief energy with probable neotectonically active zones shown as black/white lines in Figure D. Figures A through C show the result of a gradual contrast decrease between the digital domains. Dark/black areas are relatively uplifted neotectonic blocks (+) and light/white areas are relatively downthrown blocks (-).



;ure 3. Geologically mapped faults (1) versus probable neotectonically active zones (2).

geologically mapped. The fact that SE-NW faults are much less distinct (or even "invisible") in the field to some geologists may be explained by their small displacement due to a recent activation. A very good agreement between SW-NE faults and neotectonic zones indicates applicability of the described morphometric method of relief energy analysis. Barton Springs are not accidentally located right at the intersection of two neotectonically active zones (Figure 3) of which the one with the Balcones orientation is also the longest in the study area.

REMOTE SENSING OF LINEAMENTS

A lineament is defined as a mappable simple or composite linear feature on the surface differing, distinctly from the patterns of the adjacent features and presumably reflecting a subsurface phenomenon. Although many lineaments are controlled by structural displacement, they may also represent geomorphic (physiographic) or tonal features caused by contrast difference (Morgan and Koger., 1988). A typical geomorphic lineament would be a straight stream valley, whereas a tonal lineament could be caused by differences in vegetation, moisture content or soil and rock composition (Sabins, 1987). Remote sensing, of lineaments, i.e. faults/fractures as probable preferential flow paths of groundwater, is a well established and practically an obligatory procedure in karst hydrogeology studies in many countries (Kresic and Pavlovic, 1990).

Lineament analysis was performed on the Landsat MSS image which was digitally processed, enhanced and filtered using Adobe Photoshop (Busbey et al., 1992). Figure 4 shows the red (single) band scene of a part of the study area west of Barton Springs after it was stretched and adjusted for the brightness/contrast. The red band appeared to be the most suitable for the analysis of lineaments since it carries the least visual noise from the urban and agricultural features. For the initial fracture/fault mapping the scene was filtered in Adobe Photoshop using a variety of built-in and external directional and non directional convolution filters. Figure 5 shows the result of a gradient 3 by 3 kernel filtering, that has greatly enhanced the lineament pattern. In deciding which lineament is a potential fault/fracture, i.e. for the exclusion of obvious man-made features (roads, power lines, agricultural boundaries, etc.), the filtered scene was each time compared with the original R,G,B image. Three different fracture patterns are emphasized by the filtered image shown in Figure 5. The traces of lineaments are shown in Figure- 6 together with the rose diagram of their orientation. The statistical maxima of the three systems highly agree with the orientations of both geologically mapped faults and neotectonically w active zones.

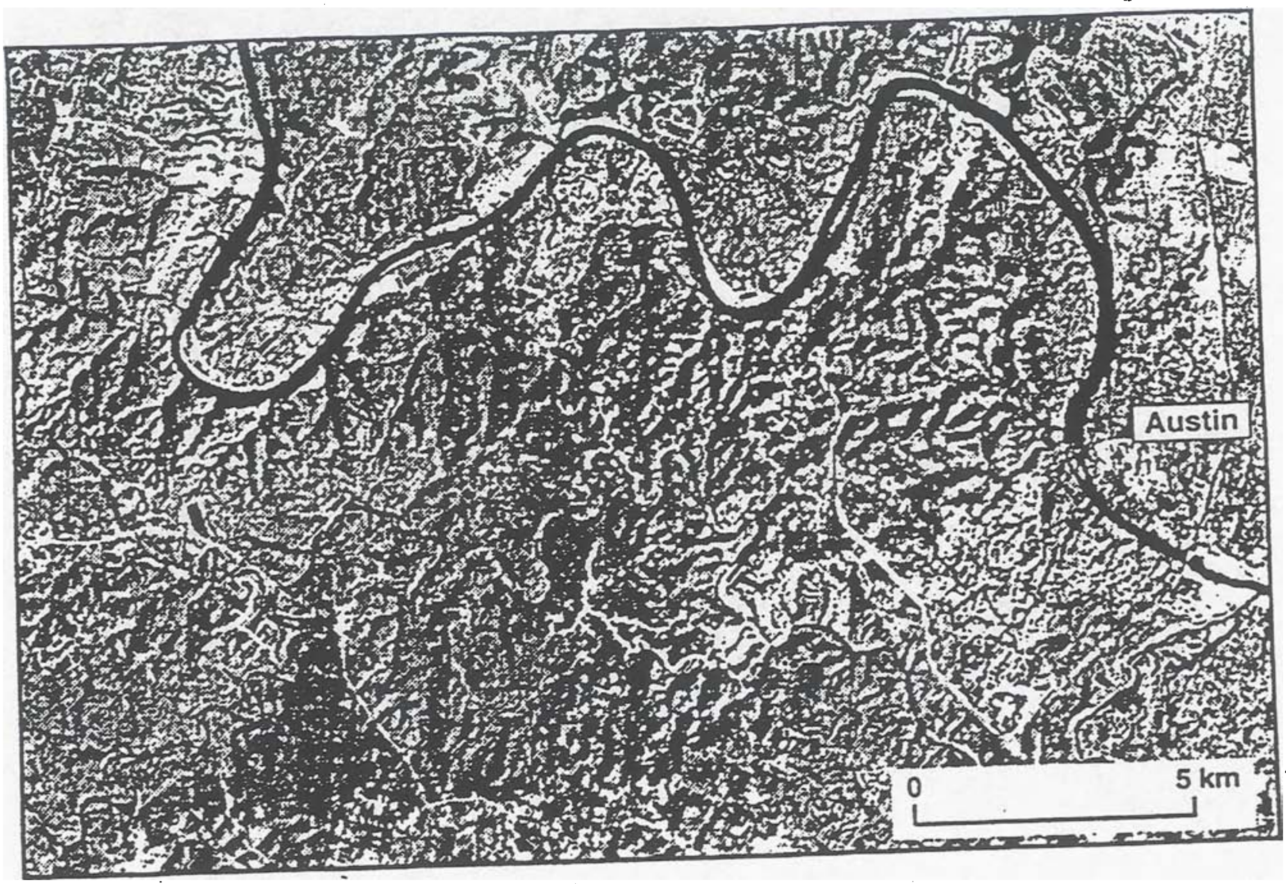


Figure 4. Landsat MSS image (red channel) of the area west of Barton Springs

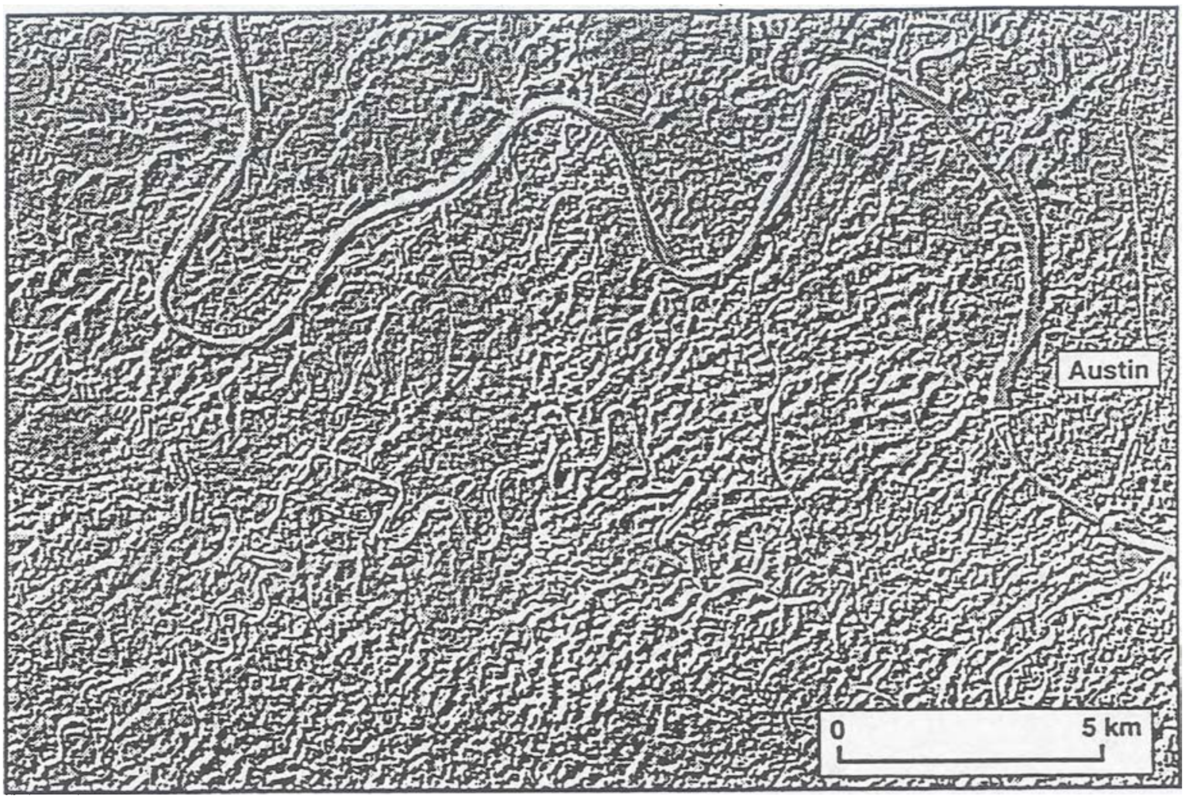


Figure 5. Landsat MSS image filtered for the lineament analysis.

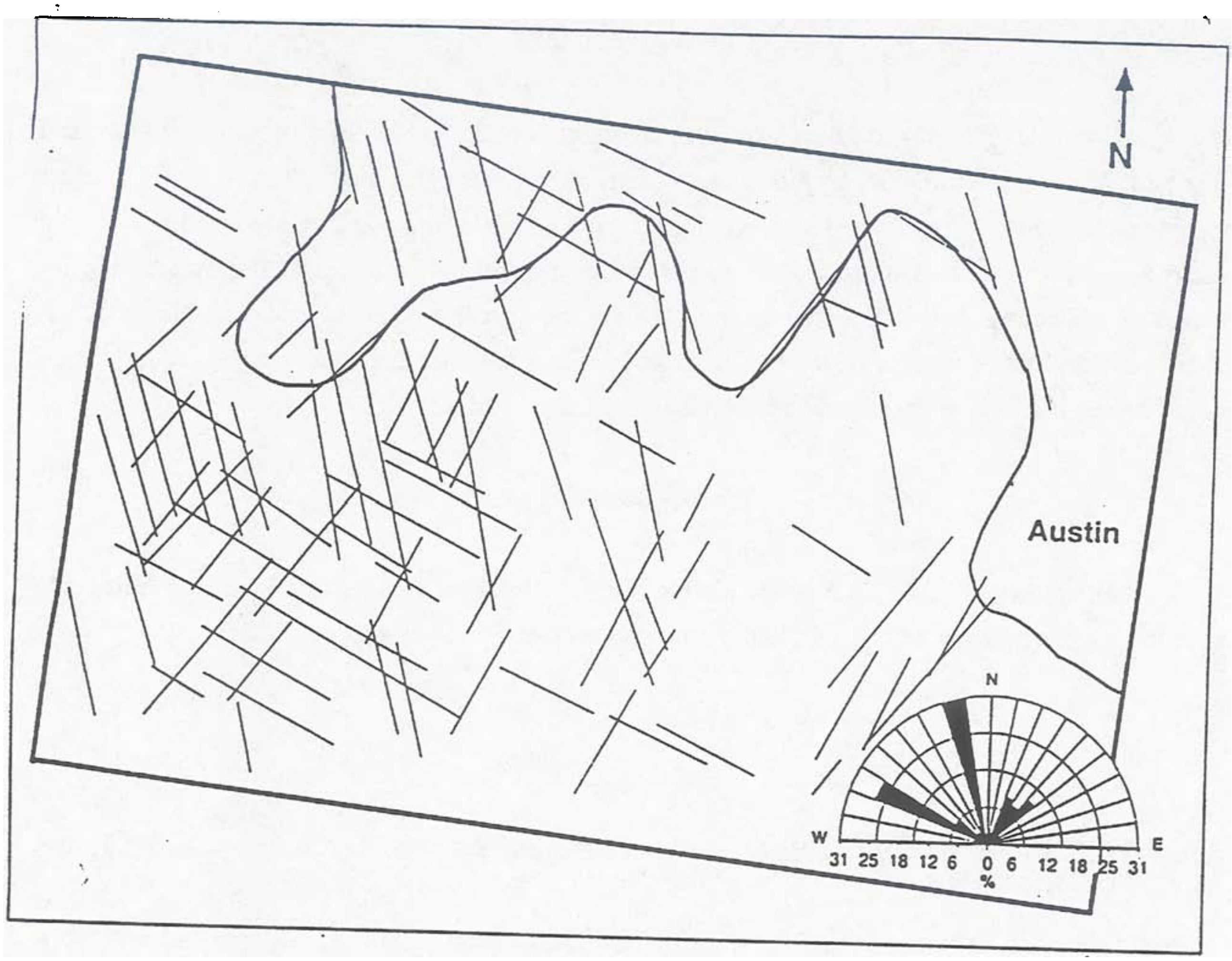


Figure 6. Orientation of the three main systems of lineaments in the area west of Barton Springs shown on Figures 4 and 5

CONCLUSIONS

Morphometric neotectonic analysis, in conjunction with remote sensing of lineaments, is a fast and inexpensive tool for the preliminary study of possible groundwater flow paths in karst terranes. The utilization of USGS Digital Elevation Models and various affordable software packages enable application of the method of relief energy for the large areas. The method is very useful for indicating, potential recent tectonic activity that is still without a clear geologic reflection at the surface. Delineation of neotectonically active zones and blocks is also a good ground for an initial conceptualization in groundwater modeling of karst aquifers.

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RUNOFF DETERMINATIONS IN THE ONION CREEK WATERSHED: A RECONSIDERATION

by

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Introduction

A modified Soil Conservation Service (SCS) method developed by HDR Engineering was used to quantify runoff from an intervening area within the Onion Creek watershed near Austin, Texas. This method was compared to the United States Geologic Survey's (USGS) previous efforts to determine runoff. Streamflow measurements from April, 1981 were arbitrarily selected to compare results from both methods.

Hydrologic Context

The Onion Creek watershed is the largest of six watersheds covering the Barton Springs segment of the Edwards aquifer (Barton Springs segment). The Barton Springs segment is a highly productive karst aquifer located in northern Hays and southern Travis Counties, and the source of water for over 35,000 people (Bill Couch, personal communication). In addition to water wells, discharge occurs through Barton Springs in Austin, Texas. Barton Springs is a popular swimming "hole" that also provides habitat for the Barton Springs salamander, which is proposed for listing as an endangered species by the United States Fish and Wildlife Service. At different times, spring discharge also accounts for a significant portion of the base flow in Town Lake; consequently, it serves as a source of water for the City of Austin and other communities located downstream (BS/EACD, 1992).

The Barton Springs segment is replenished, or recharged, through the downward migration of surface water. Recharge occurs primarily in the beds of six creeks that cross a region of the aquifer with fractured and faulted limestone exposed at the surface. This region is known as the recharge zone. Onion, Bear, Little Bear, Slaughter, Williamson, and Barton Creeks are ephemeral streams, and along with their tributaries, provide most of the water available for recharge. The majority of this water is runoff originating in the contributing zone, which is that portion of each creek's watershed above the recharge zone.

Previous Efforts

Previous efforts to determine runoff available for recharge in the Barton Springs segment relied upon a method developed by the USGS. Gaging stations are set up above and below the recharge zone to measure streamflow. In the Onion Creek watershed the upstream gaging station is located near Driftwood along the western edge of the recharge zone and the downstream gaging station is located near Buda along the eastern edge of the recharge zone. The area between stations is referred to as an intervening area and includes all of the recharge zone as well as a small portion of the contributing zone. The volume of recharge is the difference between streamflow from the gaging stations above and below the recharge zone plus runoff from the intervening area. Runoff from the intervening area is estimated on the basis of unit runoff from the area upstream of the recharge zone (Slade, 1985).

The USGS collected streamflow measurements from streams crossing the Barton Springs segment of the Edwards aquifer from July, 1979 through December, 1982. In April, 1981 the USGS measured 2920 ac-ft from the Driftwood gaging station (Slade, 1985). The watershed upstream from the gaging station is 124 square miles. Using the USGS method to determine runoff yielded 23.55 ac-ft/mi^2. Applying this unit factor to the intervening area, which is 42 mi^2, yielded a total of approximately 989 ac-ft for April, 1981.

Methodology

Because it can not be measured directly, calculating runoff from an intervening area is one of the most difficult parameters to quantify. Runoff volume is part of an equation that is used to determine recharge, which if underestimated could lead to erroneous assumptions about the carrying capacity of our groundwater resources.

HDR Engineering developed a method to estimate runoff from an intervening area within the San Antonio segment of the Edwards Aquifer. Their method is a variation of an SCS procedure that utilizes a runoff curve number (CN) to quantify runoff on a monthly rather than storm event basis. A CN is an empirical rating of the hydrologic performance of a large number soils and land-use/vegetation covers throughout the United States (Dunne and Leopold, 1978). Unlike the USGS, the SCS has taken soil types, land-use/vegetation covers, and differences in precipitation between the upstream and intervening areas into account to determine runoff volumes (HDR, 1994).

Curve Number Determinations.

Curve numbers (AMC_{II}) were obtained by placing soil associations containing similar hydrologic soil groups together, averaging their curve numbers, and applying an average value throughout the recharge and contributing zone. Each CN is weighted by area to determine its relative contribution. Weighted values are summed and a single value is applied to the contributing zone and intervening area. By rounding, CNs (AMC_{II}) were obtained for the contributing zone and the intervening area, which are 80 and 79, respectively. Table I illustrates each CN, its location, area, and relative contribution.

Table I - Curve Numbers For The Contributing And Intervening Areas

Contributing Zone			Intervening Area		
CN	Area (mi^2)	Contribution	CN	Area (mi^2)	Contribution
80.00	113.76	73.60	74.00	0.64	1.48
79.00	10.24	6.32	76.00	0.80	1.52
			77.00	1.76	3.08
			78.00	36.40	67.86
			80.00	2.40	4.80
Total	124.00	79.92		42.00	78.74

Table 10.1 in Section 4 of the SCS's National Engineering Handbook (NEH4) was used to determine CNs under other soil moisture conditions (SCS, 1972). By inspection, the AMC_I and AMC_{III} CN values for the contributing zone are 63 and 91, respectively. While for the intervening area, they are 62 and 91, respectively.

Rainfall - Runoff Relationships

To calculate runoff from the intervening area, a CN must be calibrated for antecedent moisture conditions in the watershed above the upstream gaging station (HDR, 1994). The calibration procedure is necessary to justify application of SCS methods on a monthly rather than storm event basis. The calibration assumes that antecedent moisture conditions in the watershed upstream are similar.

Streamflow totaling approximately 2920 ac-ft was measured at the Driftwood gaging station in April, 1981. Rainfall collected at the station measured 1.27 inches. Solving,

2920 ac-ft/124 square miles x 1 square mile/640 acres x 12 inches/foot, yielded 0.44 inches of runoff. The CN illustrated in Figure 10.1 - 1 from the SCS's NEH4 is 88, which is between AMC_{II} and AMC_{III} for the contributing zone. By interpolation, using AMC_{II} and AMC_{III} for the intervening area yielded a CN of 85.73, which was rounded to 86 and is the calibrated CN. Using an equation defined in the SCS's NEH4, a p = 1.43" measured at the Buda gaging station for April 1981, and the calibrated CN, solve the following equation to determine runoff from the intervening area:

$$QI = (640/12)\,A \frac{(P - 200/CN + 2)^2}{(P - 800/CN + 2)}$$

where:

QI	= Runoff from the intervening area;
A	= Watershed area (square miles);
P	= Precipitation (inches/month); and
CN	= SCS Curve Number.

Runoff from the intervening area equals 1001 ac-ft for April 1981.

Conclusion

The modified SCS method's results closely approximate the USGS's for runoff from the intervening area in the Onion Creek watershed. The close approximation between runoff values may be attributed to the similarity between hydrologic soil properties as evidenced by the AMC_{II} CNs and rainfall in the contributing zone and intervening area.

With greater variation between such factors as hydrologic soil groups, rainfall, and impervious cover, results from the modified SCS method could diverge significantly from those obtained using the USGS method. Impervious cover was not taken into account; however, Onion Creek is only slightly developed. Future studies should account for natural and manmade impervious cover and incorporate data obtained at a higher resolution for soil types and vegetative/land-use covers.

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