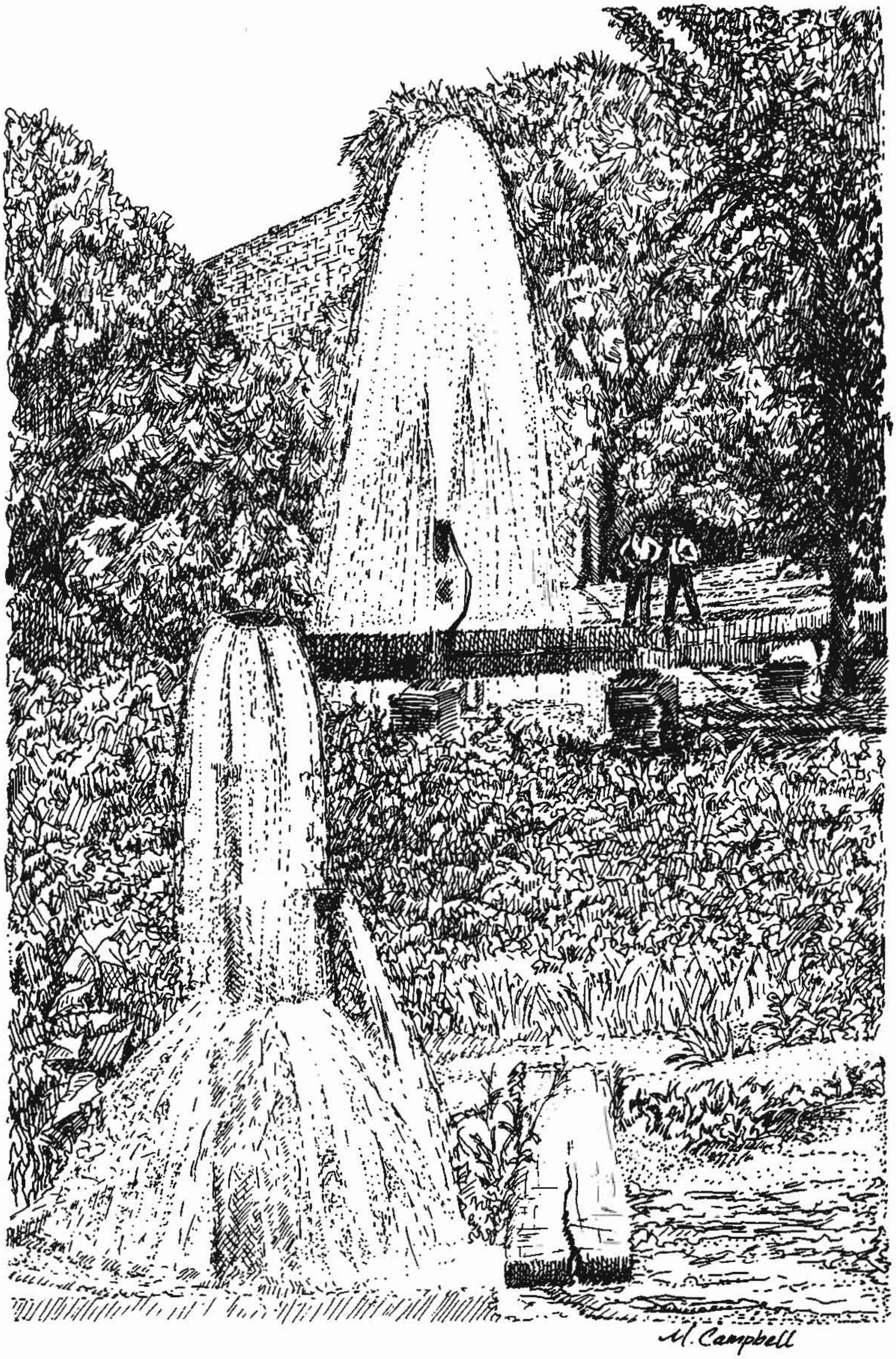
THE BALCONES ESCARPMENT



Edited by PATRICK L. ABBOTT and C.M. WOODRUFF, Jr.
1986

THE BALCONES ESCARPMENT

Geology, Hydrology, Ecology and Social Development in Central Texas

Editors

PATRICK L. ABBOTT
Department of Geological Sciences
San Diego State University
San Diego, California 92182

C.M. WOODRUFF, JR.
Consulting Geologist
P.O. Box 13252
Austin, Texas 78711

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For copies of this book please write or phone:
PATRICK L. ABBOTT
Department of Geological Sciences
San Diego State University
San Diego, California 92182-0337
(619) 265-5591

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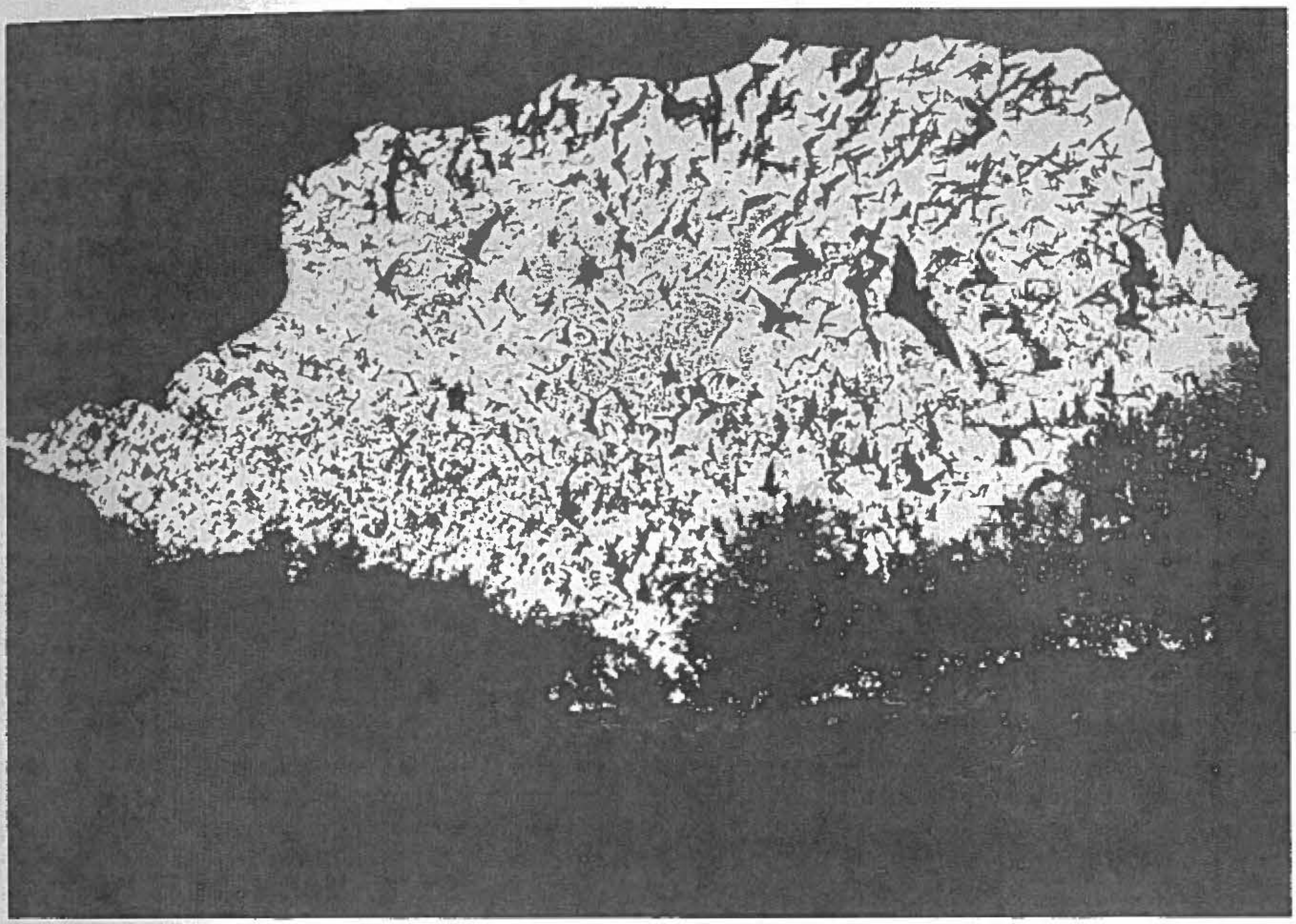

124p-USBWF: The twilight emergence of Mexican Free-tailed Bats (*Tadarida brasiliensis*) from the entrance of Bracken Cave. This is one of nature's most spectacular events. Young bats of this species first fly in about 4-5 weeks. Adults attain speeds of more than 40 miles per hour and may cover hundreds of miles in a single night.

Up to 9 million of these bats once inhabited Carlsbad Caverns, but the colony has been reduced to a mere 300,000. The largest colony of Mexican Free-tailed Bats ever known has declined by an alarming 99% in only two decades. These, like most other bats, are highly beneficial, essential to a healthy environment, and deserving of our utmost respect and consideration.

Photograph courtesy of Merlin D. Tuttle, Bat Conservation International.

FRONT COVER: Artesian wells, City Waterworks, San Antonio, circa 1897 from photograph in Hill and Vaughn (*plate 39, 1897, U.S. Geological Survey Annual Report*).

Drawing by Margaret Campbell.

PREFACE

The Balcones Escarpment is a line of low hills that extends through Central Texas. As pointed out by Fenneman in his classic Physiography of Western United States, this escarpment marks the break between two grand physiographic divisions of North America: the Great Plains Province on the west and the Coastal Plains on the east. In Central Texas this major physiographic break is denoted by the change from Hill Country/Edwards Plateau uplands on the western side of the escarpment to the Blackland Prairie on the east (Fig. 1). The Balcones Escarpment lies along the major line of dislocation of the Balcones fault zone, a series of *en echelon* mainly down-to-the-coast normal faults. Fault displacements have resulted in Lower Cretaceous limestones to the west being juxtaposed against Upper Cretaceous claystones, chalks, and marls to the east.

The Balcones fault zone is a surface expressi of a deep-seated crustal discontinuity. The Ouachita orogen extends southward from the Arbuckle/Ouachita juncture in Oklahoma beneath Central Texas to the Rio Grande where the orogen i displaced laterally into Trans-Pecos Texas. The Ouachita complex forms a hinge between the stable continental interior and the still-subsiding Gulf Coast basin (Fig. 2). Balcones faulting was probably a result of periodic adjustments across this buried hinge.

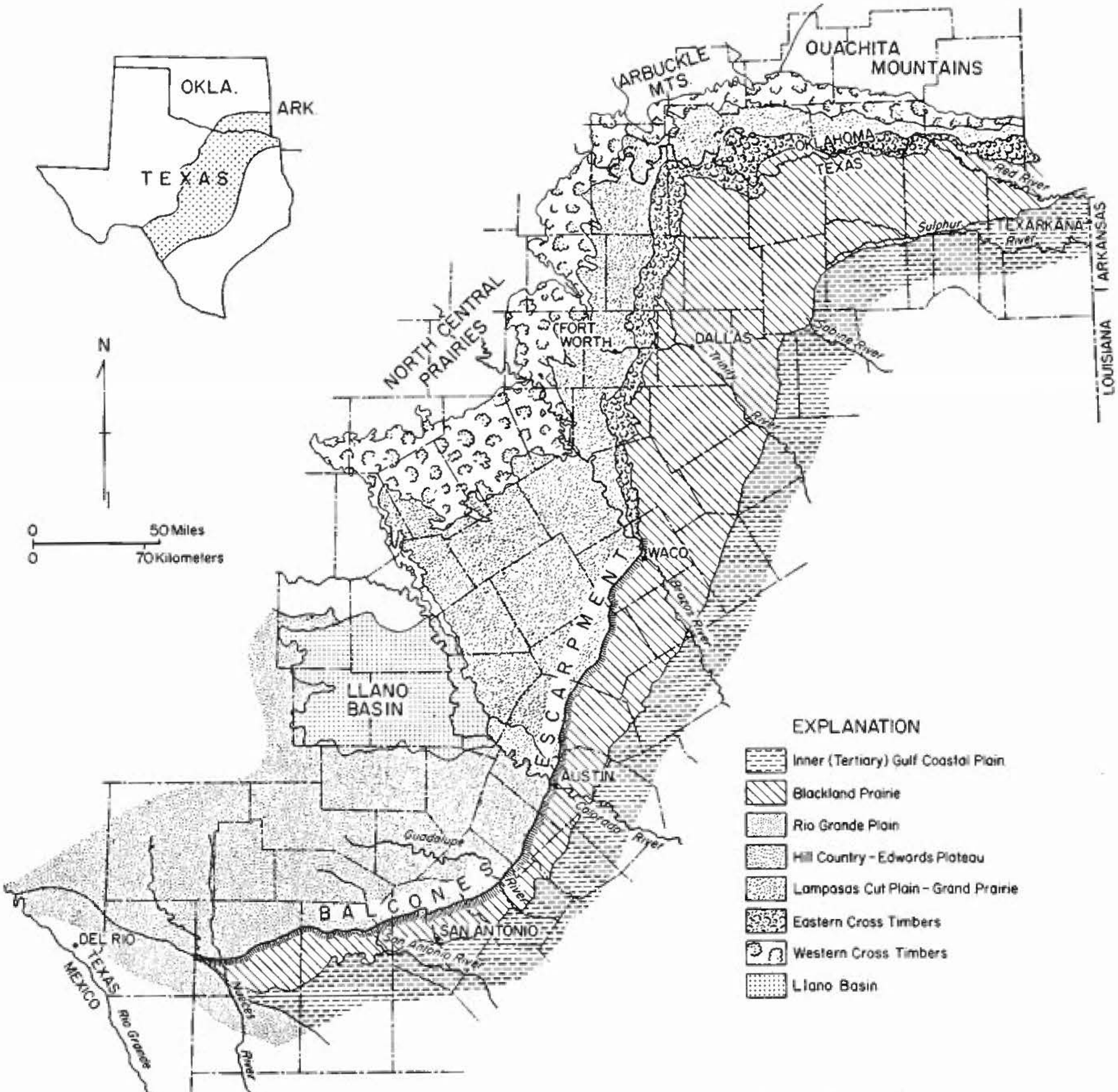

Figure 1. Physiographic provinces along the Balcones/Ouachita trend, Central Texas (figure courtesy of Bureau of Economic Geology, The University of Te at Austin).

The main tectonic events of Balcones faulting are generally thought to have occurred during the Miocene, but there is considerable evidence that periodic structural adjustments also took place in the Cretaceous. For example, mafic alkalic volcanic plugs of Late Cretaceous age occur at the surface and in the subsurface all along the Balcones fault zone. The geochemistry and petrology of these igneous rocks suggest that they penetrated the entire crust of the Earth.

Dramatic changes in the landscape occur across this crustal discontinuity. On the west are plateau uplands and ruggedly dissected limestone hills; soils are thin and stony, and the main agricultural use of the land is for range; the dominant native vegetation assemblage is juniper-live oak savannah; and groundwater is generally of good quality with ample quantities occurring at shallow depths from limestone aquifers. On the east side of the escarpment, terrain consists of rolling prairies and

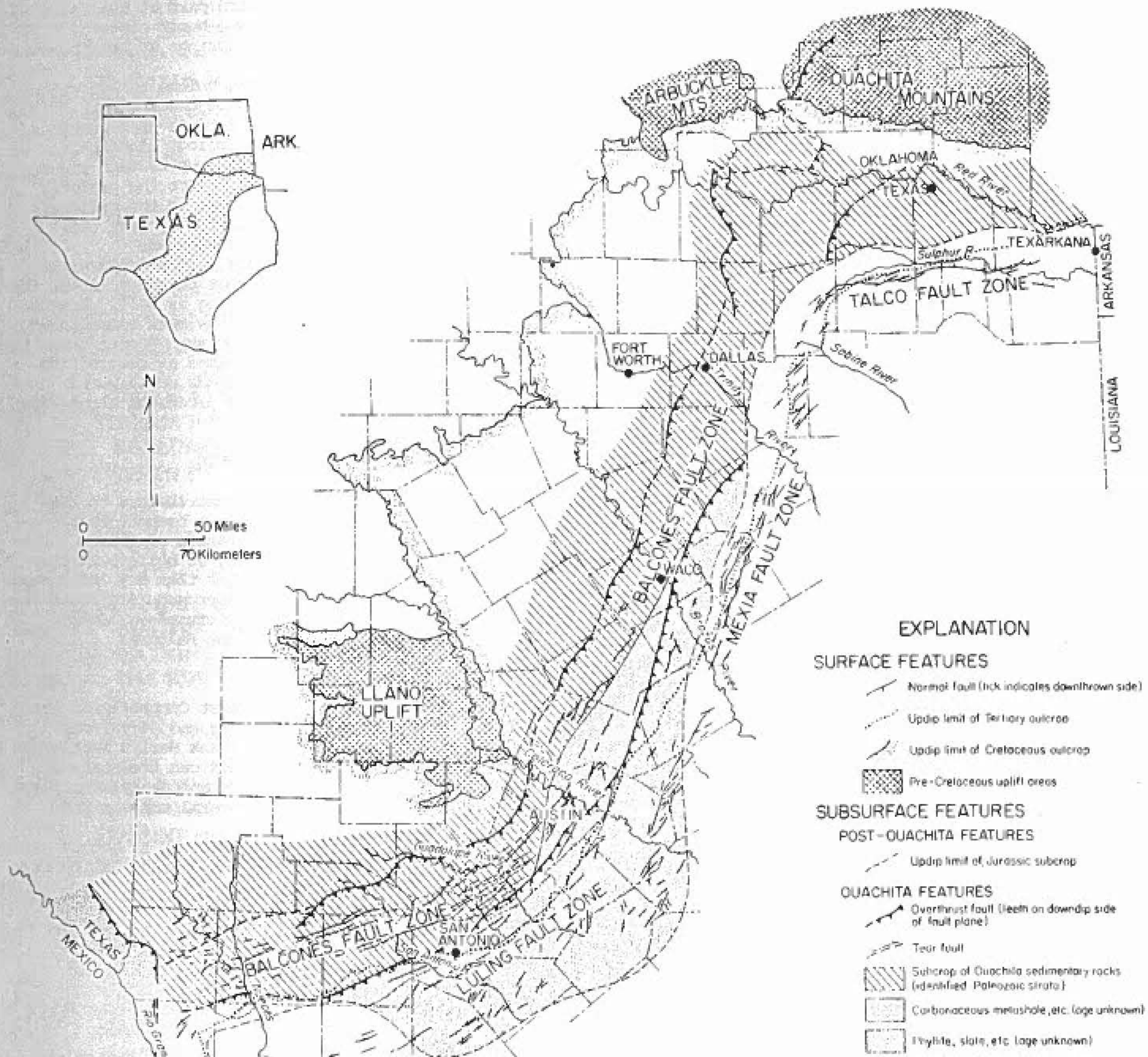

Figure 2. Structural/tectonic features along the Balcones/Ouachita trend, Central Texas (figure courtesy of Bureau of Economic Geology, The University of Texas at Austin.

broad river bottoms; soils are thick fertile clays, which compose prime arable land; native prairie grasses were dominant before the agricultural activities supplanted them; and groundwater in large amounts is available only at considerable depth and is commonly tepid and brackish.

The escarpment is also a major weather-maker. Maximum relief is only a few hundred feet, but it is the first topographic break inland from the Gulf of Mexico and thus acts as an orographic influence on unstable, water-laden air masses. These combined factors have resulted in the Balcones Escarpment being the locus of the largest flood-producing storms in the conterminous United States. The greatest single rainfall event ever recorded in the contiguous U.S. occurred in 1921, when 38 inches of rain fell in 24 hours near Thrall in Williamson County.

Physiographic changes have had their impact on human culture as well. As pointed out by Peter T. Flawn in his article "The Everlasting Land" (in A President's Country, Shoal Creek Press, 1964), the Balcones Escarpment marks the line where the American West really begins. It marks the boundary between the cotton economy of the Old South and the cattle economy of the Old West. This geocultural break has been the site of many major towns and cities in Texas: Del Rio, San Antonio, Austin, Temple, Waco, and (in its broader geographic context) Dallas/Fort Worth and Sherman/Denison. The cities are a response to the geologic break in the same way that geologic changes along the Fall Line of the eastern United States created favorable sites for industry and commerce. People settled along the Balcones Escarpment in order to draw on both economies--cotton and cattle. Also, their endeavors were aided by the dependable water supplies provided by the great springs that issue forth along the fault zone.

A dramatic expression of the Balcones/Ouachita discontinuity is the localization of the Edwards aquifer. The Edwards aquifer is composed of karstified groundwater reservoirs that extend along the Balcones Escarpment in Central Texas and west beneath the vast Edwards Plateau. The Edwards Limestone, the main host rock of the aquifer, once extended unbroken across much of Texas--from the middle part of the Gulf Coastal Plain to the Panhandle and Trans-Pecos regions. This once-continuous rock unit has been flexed and broken by tectonic events, dissected by erosion, and dissolved by the actions of percolating water. The vagaries of erosion and of structural deformation have resulted in different hydrodynamic regimes within different geologic/geographic provinces. In areas where the Edwards Limestone crops out, groundwater occurs under water-table conditions. Down dip within the fault zone, a confined zone of groundwater occurs. Farther downdip, water qualit changes abruptly across a "bad-water line" that marks the edge of upwelling deep-basin waters. Locally within the Gulf Coast basin, the Edwards Limestone is a reservoir rock for hydrocarbons.

The Balcones fault zone is where the Edwards aquifer is most prolific. There, faults have provided major avenues for directional porosity an permeability, and these conduits have been enlarge by solution so that great volumes of water flow rapidly from west to east along the escarpment. I this way, the semi-arid western part of the fault zone provides water for the sub-humid eastern watersheds where the largest springs in Texas occu

It is the purpose of this volume to present multidisciplinary information on the Balcones Escarpment. The main focus of these presentations will be on the geology and hydrology along this major break, but there are also papers that treat biological and cultural responses to the geologic features and hydrologic processes in the region. This multidisciplinary approach reinforces the message that the manifold resources are interrelated: geology affects landform and soils and plants and animals. Weather patterns affect t geomorphic and ecological setting as well. Humans have acted in context of what has been established by these natural processes from prehistoric times the present. This volume is aimed at recognizing the controls so that modern humans can live in harmony with the resources and processes along thi borderland.

ACKNOWLEDGMENTS

First, we thank all the contributors to this volume. These men and women have brought their expertise to bear on various facets of this important region. In doing so, we believe that a whole is created that is greater than any individu part. The multidisciplinary approach reinforces t unity of processes--the "big picture"--evident through space and time along the Balcones Escarpment.

We especially thank Margaret Campbell for her art work used on the front cover and at various places in the text. We also thank Merlin Tuttle fc the use of his photograph of Mexican free-tailed bats emerging from Bracken Cave and Kathy Jessup ar Marylou Montross for typing several manuscripts.

C. M. Woodruff, Jr.
Austin, Texas

Patrick L. Abbott
San Diego, Californi

September 1986

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COMAL SPRINGS--NEW BRAUNFELS

FLOODING ALONG THE BALCONES ESCARPMENT, CENTRAL TEXAS

S. Christopher Caran
Bureau of Economic Geology
The University of Texas at Austin
Austin, TX 78713

Victor R. Baker
Department of Geosciences
University of Arizona
Tucson, AZ 85721

A few days before the rains began to fall, a band of Tonkawa Indians that were camped in the river valley just below old Fort Griffin moved their camp to the top of one of the nearby hills. After the flood, on being asked why they moved to the top of the hill, the chief answered that when the snakes crawl towards the hills, the prairie dogs run towards the hills, and the grasshoppers hop towards the hills, it is time for the Indian to go to the hills. (Oral testimony attributed to an unnamed weather observer in Albany, Texas, following a memorable flood on the Clear Fork of the Brazos River in the late 1870's; recounted by Vance, 1934, p. 7.)

ABSTRACT

High-magnitude floods occur with greater frequency in the Balcones Escarpment area than in any other region of the United States. Rates of precipitation and discharge per unit drainage area approach world maxima. The intensity of rainstorms is compounded by rapid runoff and limited infiltration, producing episodic flooding. Effects of urbanization may be superimposed on meteorologic and physiographic factors, thereby increasing flood hazards in metropolitan areas throughout the region.

INTRODUCTION

The Balcones Escarpment area, comprising parts of the Edwards Plateau, Hill Country, and northern and westernmost Coastal Plains (fig. 1), is one of the most severely flooded regions of the United States (Leopold and others, 1964, fig. 3-16; Baker, 1975; Beard, 1975, fig. 13; Crippen and Bue, 1977, fig. 12, table 1; Patton and Baker, 1976, p. 945, fig. 5). Floods of record include the catastrophic 1954 inundation of the lower Pecos River valley where peak instantaneous discharge approached 1,000,000 cubic feet per second (cfs), or more than 600 billion gallons per day (International Boundary and Water Commission, 1954). This reach of the Pecos normally is an intermittent stream completely dry for several months each year. But during the 1954 event, its rate of discharge was more than 1 1/2 times mean flow of the world's third longest river, the Mississippi (table 1). What's more, only part of the Pecos drainage basin had received significant rainfall and provided runoff; the contributing area was less than 0.3 percent of the Mississippi's watershed.

The 1954 Pecos River flood was a remarkable occurrence, estimated to represent the 2,000-yr recurrence interval flood (0.05 percent yearly-probability flood) in that basin (Kochel and others, 1982, p. 1179). This and other major discharge events are easily and instructively compared by examining the ratio of peak discharge (in cfs) to contributing drainage area (in mi^2). During the 1954 flood of the Pecos, this ratio was approximately 261:1, compared to 0.5:1 for mean discharge of the Mississippi (table 1). Although the rate of peak discharge of the Pecos was exceptional, floods yielding comparable discharge:drainage area ratios have been recorded in most drainage basins and subbasins in Central Texas. Intense rainstorms over small watersheds throughout the region have produced numerous examples of discharge in excess of 100,000 cfs. Flooding of this magnitude exacts a heavy toll from area residents who incur the high cost of flood-control structures on trunk streams (fig. 1), but also sustain casualties and damages associated with floods on small, unregulated or under-regulated tributaries.

CAUSE OF MAJOR FLOOD EVENTS

Baker (1975; 1977) and Patton and Baker (1976) described a number of factors that contribute to flooding in the Balcones Escarpment area. Principal among these are: (1) the intensity of sporadic rainstorms, particularly those associated with incursions of tropical storms and hurricanes; and (2) the high-percentage yield and rapidity of runoff from the steep bedrock slopes that characterize much of the region. (NOTE: Meteorologic conditions in the Central Texas region are discussed in greater detail in another section of this guidebook and in references cited here.) To these factors may be added the many drainage problems inherent in urban areas including large municipalities along the Balcones Escarpment (fig. 1). Although not unique to Central Texas, the role of urbanization in flood enhancement is especially significant when superimposed on adverse characteristics of the natural environment of this region.

Meteorologic Factors

<u>Easterly Waves</u>

The climatic provenance and topography of Central Texas, and its proximity to the Gulf of Mexico, combine to make the incidence of torrential rains in the area extremely high. The region lies within the zone of convergence of polar air masses and easterly waves (Orton, 1966, p. 10-11). Polar air is characterized by cool temperatures, high pressures, and low moisture. Easterly waves, which are westward-moving troughs of low pressure, convey warm, moist air of tropical origin. When a well-developed easterly wave approaches a lobe of high-pressure, such as that associated with a strong polar surge into middle latitudes, pronounced instability and heavy rains may result.

in Abbott, Patrick L. and Woodruff, C.M., Jr., eds., 1986, **The Balcones Escarpment, Central Texas:** Geological Society of America, p. 1-14

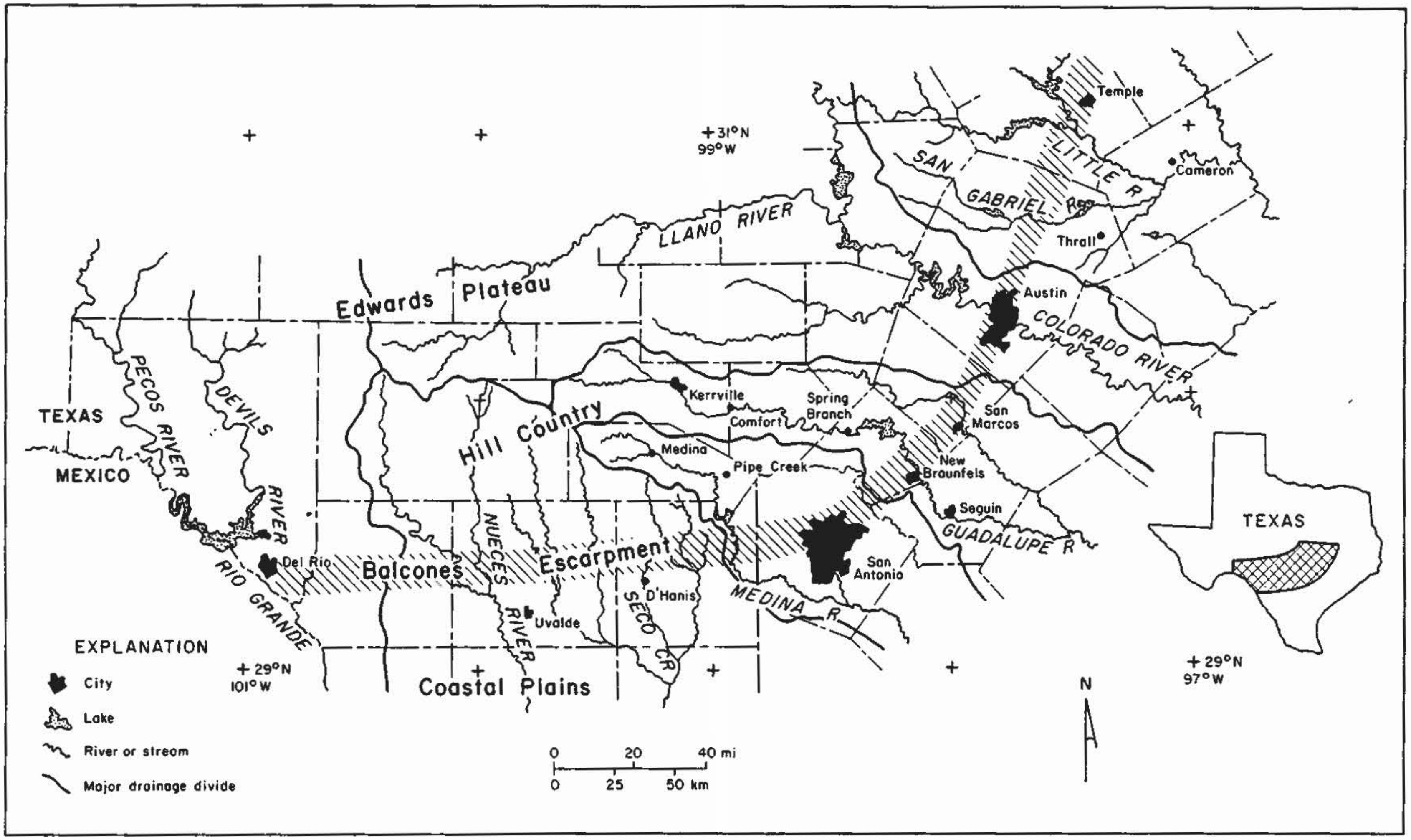


Figure 1. Balcones Escarpment area, Central Texas. Only major streams and those mentioned in text are named. Relief across the Balcones Escarpment varies from 100 to 500 ft.

Table 1. Representative flood discharge of Central Texas streams compared with mean discharge of some of the world's great rivers

River/stream	(A) Drainage area (x 10^3 mi^2)	(B) Discharge (x 10^3 cfs)	Ratio B:A
Amazon[1]	2,722.[a]	4,200[b]	2:1
Nile[2]	1,293.[a]	110[b]	0.1:1
Mississippi-Missouri[3]	1,243.7[a]	620[b]	0.5:1
Texas			
(Source: International Boundary and Water Commission, 1954; Crippen and Bue, 1977; Schroeder and others, 1979; Moore and others, 1982)			
Pecos (U.S. Hwy 90, 1954)	3.7[c]	967[d]	261:1
Little (Cameron, 1921)	7.1[c]	647[d]	91:1
North Prong of Medina (Medina, 1978)	0.07[c]	123[d]	1,800:1
Medina (Pipe Creek, 1978)	0.5[c]	281[d]	600:1
Guadalupe (Comfort, 1978)	0.8[c]	240[d]	300:1
Guadalupe (Spring Branch, 1978)	1.3[c]	158[d]	122:1
Seco (D'Hanis, 1935)	0.14[c]	230[d]	1,500:1
Walnut (FM Hwy 1325, 1981)	0.01[c]	15[d]	1,500:1

[1] World's largest drainage area and discharge; second longest
[2] World's longest; fourth largest drainage area; tenth largest discharge
[3] World's third longest; fifth largest drainage area and discharge
(Source: National Oceanic and Atmospheric Administration, 1971)

[a] Entire basin
[b] Mean discharge at mouth
[c] Contributing portion of drainage area
[d] Flood discharge at point of measurement

This combination is comparatively uncommon but has produced extremely heavy rains and associated flooding. The most severe rainstorm ever recorded in the continental United States occurred under these conditions on September 9 and 10, 1921, in Thrall, Williamson County (Jennings, 1950; Bowmar, 1983, p. 69) (fig. 1,2). A total of 36.4 inches of rain fell in 18 hr, which is the world's record for this period. The 24-hr total was 38.2 inches, exceeding in one day the expected precipitation of an entire year (Larkin and Bowmar, 1983, p. 18). At the town of Cameron, Milam County, a few miles northeast of Thrall, peak discharge of the Little River was 647,000 cfs from a drainage area of 7,088 mi^2 (Crippen and Bue, 1977, table 1) (figs. 1, 3; table 1). This storm, which spread over a large area of Central Texas, produced 215 deaths and 19 million dollars in property damage (Bowmar, 1983, table E-3).

Orographic Effects

The easterly wave that produced the Thrall storm of 1921 was augmented by topographic conditions in the region. Relief across most of the Balcones Escarpment ranges from 100 to 500 ft (fig. 1 caption). Warm, moisture-laden air from the Gulf of Mexico is pushed northward across the gently sloping Coastal Plains by dominant southerly winds. As these winds encounter the escarpment they rise abruptly to higher altitude. If the Gulf air is nearly saturated at lower elevations, rainstorms may occur along the escarpment because of orographic cooling of the air mass. The climate of Central Texas is semiarid; drought years offset wet periods, thereby reducing mean annual precipitation. But cumulative rainfall increases sharply at the escarpment compared to adjacent regions (fig. 4), and rains may be extremely intense for periods of

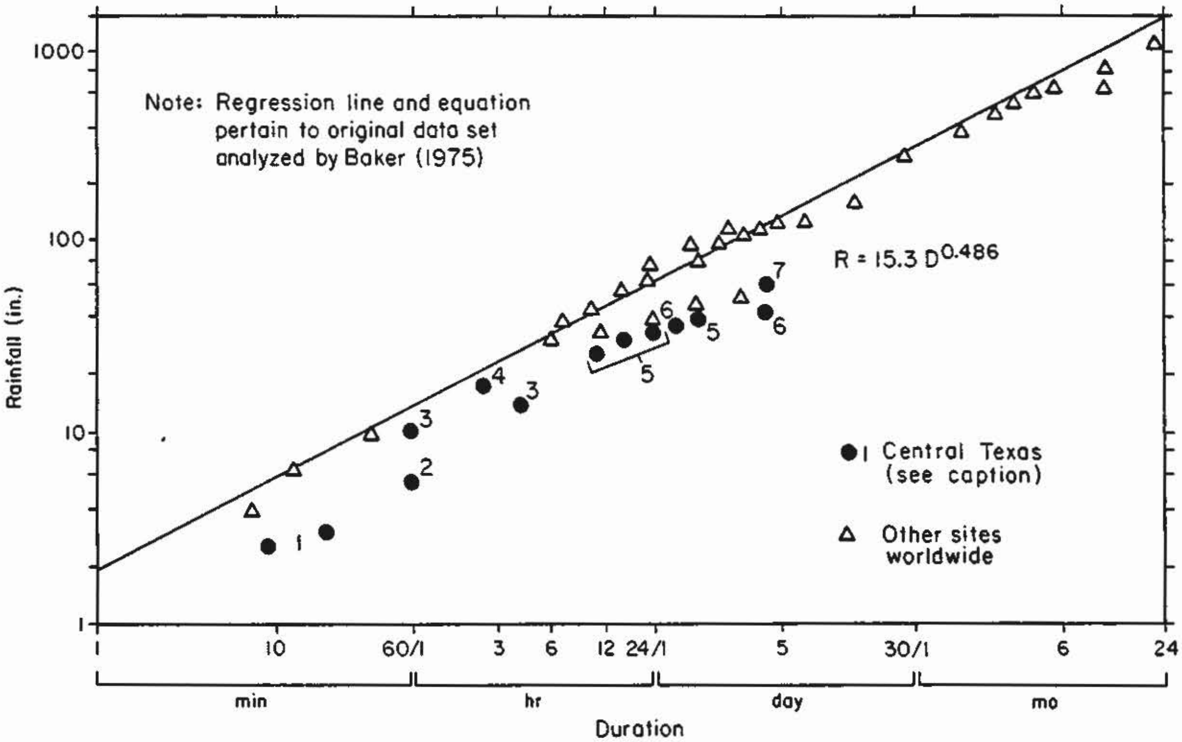


Figure 2. Magnitude-duration relationships of the most intense rainstorms in Central Texas and the rest of the world. Sites in Central Texas: (1) Trough Creek, 1973; (2) Austin, 1981; (3) New Braunfels, 1973; (4) D'Hanis, 1935; (5) Thrall, 1921; (6) Voss Ranch, 1978; (7) Manatt Ranch, 1978. Adapted from Baker (1975, fig. 2). Additional data sources: Hansen (1979); Massey and others (1982, table 2); Moore and others (1982, figs. 2.2, 2.4); and sources cited by Baker (1975, fig. 2).

hours to days over small areas (Carr, 1967, p. 20-21; Bowmar, 1983, p. 56). An astonishing example of this orographic effect is the storm of May 31, 1935, near D'Hanis, Medina County (Jennings, 1950; Morgan, 1966, p. 37, 40) (fig. 2). A total of 22 inches of rain fell in just 2 hr and 45 min, which is the world-record precipitation for that period. At a point a few miles above D'Hanis, Seco Creek has a drainage area of only 142 mi^2 yet briefly discharged at a rate of 230,000 cfs (Crippen and Bue, 1977, table 1) (table 1; fig. 3).

Tropical Disturbances

Tropical storms and hurricanes are regular seasonal occurrences over the warm waters of the Caribbean and Gulf of Mexico. Their paths do not often extend far inland but occasional storms penetrate well into the interior of the state and beyond. Some of the Central Texas region's heaviest rainfalls are products of these events. A recent example is tropical storm Amelia, which produced catastrophic flooding throughout the area in August, 1978. The largest three-day total rainfall ever recorded in the United States occurred on the Manatt ranch, Medina County, where more than 48 inches of rain fell during the period August 1 to 3 (Hansen, 1979) (fig. 2). Near this ranch, on the North Prong of the Medina River, peak discharge was 123,000 cfs from a drainage area of 67.5 mi^2 (Schroeder and others, 1979, p. 6) (table 1; fig. 3). Farther downstream, discharge of the Medina River near Pipe Creek was 281,000 cfs from a drainage area of 474 mi^2 (Schroeder and others, 1979, p. 111). Medina Lake near San Antonio overflowed its spillway as storage increased by 93,000 acre-feet in 35 hr (Schroeder and others, 1979, p. 6). Flood stages at 13 stations excee previous records and/or projected stages of floods with recurrence intervals greater than 100 yr (Sullivan, 1983 47).

Physiographic Factors and Urbanization

Climatic factors control precipitation but once rai reaches the ground it is the character of the land itsel that controls runoff. The Balcones Escarpment area h steep sparsely-vegetated slopes, narrow valleys, thin up soils on limestone bedrock, and, in the Coastal Plains, with low infiltration capacity (Baker, 1975, 1976, 1977 Patton and Baker, 1976) (fig. 5). Each of these factc increases runoff and, therefore, discharge per unit drair area. Development practices in metropolitan areas als tend to increase runoff but may reduce flow through stream channels, as well. Urbanization generally increa (1) impervious cover (that is, the areal extent of roofs parking lots, and roadways that reduce infiltration); (2 channel rectification (reduces channel storage thereby increasing discharge farther downstream); (3) channel obstruction (causes damming behind bridge abutments, water crossings, waterside recreational facilities, etc.); (4) floodplain development (inhibits high-water through (Leopold and others, 1964; Costa, 1978; Morisawa anc LaFlure, 1979; Rahn, 1984). Espey and others (1966) demonstrated that land-use practices alone can increas Central Texas peak flood discharges by as much as 3(percent.

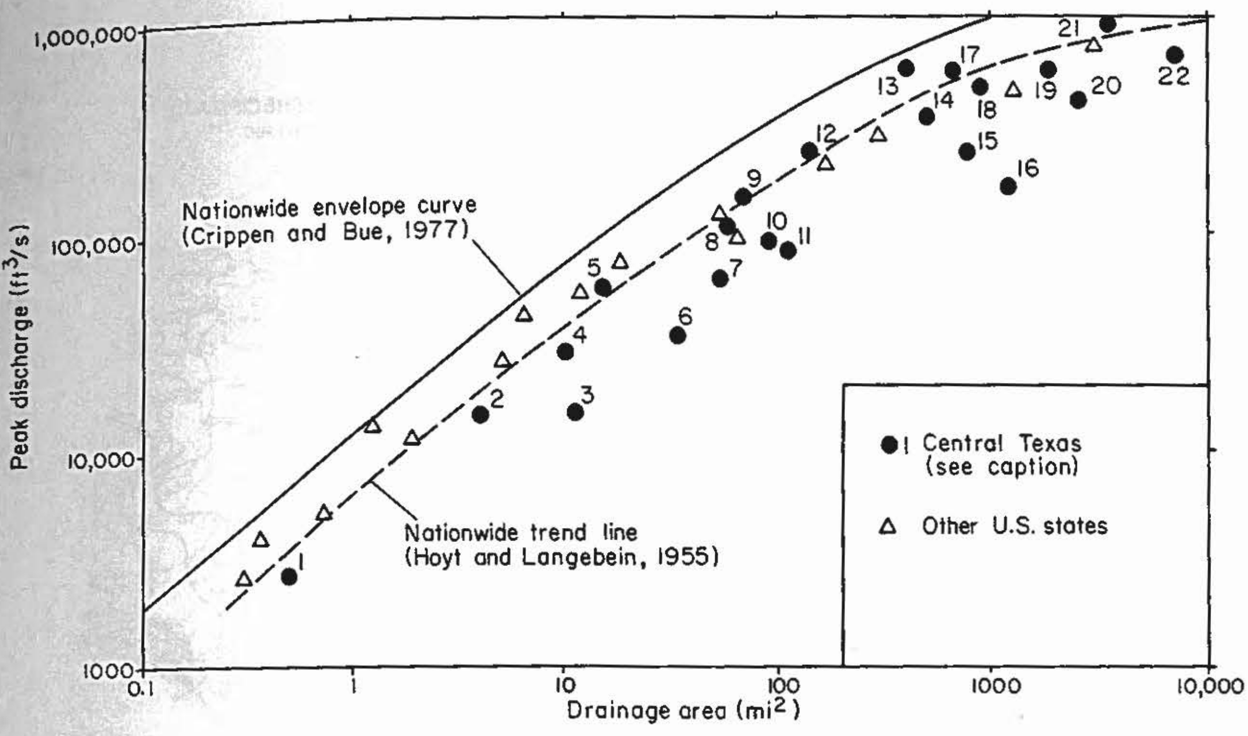


Figure 3. Discharge-watershed relationships of the most severe floods in Central Texas and other U.S. states. Sites in Central Texas: (1) Trough Creek near New Braunfels, 1972; (2) Bunton Creek at Kyle, 1936; (3) Walnut Creek at Austin, 1981; (4) Little Red Bluff Creek at Carta Valley, 1948; (5) Calaveras Creek near Elmendorf, 1946, Blieders Creek near New Braunfels, 1972, and Spring Creek near Fredricksburg, 1978; (6) Purgatory Creek near San Marcos, 1972; (7) Sink Creek near San Marcos, 1972; (8) North Prong of Medina River near Medina, 1978; (9) Mailtrail Creek at Loma Alta, 1948; (10) Guadalupe River at New Braunfels, 1972; (11) Hondo Creek near Hondo, 1919; (12) Seco Creek near D'Hanis, 1935; (13) West Nueces River near Kickapoo Springs, 1935; (14) Medina River near Pipe Creek, 1978; (15) Guadalupe River at Comfort, 1978; (16) Guadalupe River near Spring Branch, 1978; (17) West Nueces River near Brackettville, 1935; (18) Pedernales River near Johnson City, 1952; (19) Nueces River below Uvalde, 1935; (20) Devils River near Del Rio, 1932; (21) Pecos River at U.S. Highway 90, 1954; (22) Little River at Cameron, 1921. Adapted from Baker (1975, fig. 4) and Crippen and Bue (1977, figs. 2, 12). Additional data sources: Schroeder and others (1979, p. 11); Massey and others (1982, table 1); and source cited by Baker (1975, fig. 4).

Urban flooding is a serious problem in many Central Texas communities (Baker, 1975, 1976). For example, within the small, largely rural Guadalupe River basin, the Federal Emergency Management Agency has designated 17 cities with significant flood hazards (Texas Department of Water Resources, 1984, p. III-18-6). Annual flood losses throughout the Balcones Escarpment area remain high despite a network of flood-control structures (fig. 1). During the "Memorial Day" flood of May 24 to 25, 1981, the city of Austin sustained 13 deaths and 35.5 million dollars in damages from flooding along small unregulated urban streams (Moore and others, 1982, p. 15). In response, the city constructed several discharge-retention dams and completely revamped its procedures for assessing flood hazards and issuing warnings. But although this system may reduce future casualties and property losses it represents a significant infrastructural investment that few area communities could make. Better planning at an earlier stage of urban development might have prevented foreseeable problems experienced during the 1981 flood and eliminated costly retrodesign.

Urbanization merely compounds the natural tendency of Central Texas streams to produce damaging floods with greater frequency than do comparable drainage basins elsewhere. But the causes and effects of flooding in rural and urban settings differ in important ways. Two case studies, one concerning an undeveloped stream reach, the other an area undergoing urban growth, are reviewed in order to assess these differences.

CASE STUDIES

Rural Flooding: Guadalupe River, 1978

A striking example of flooding in a rural watershed is the August, 1978 event on the upper Guadalupe River, which was associated with the deep inland incursion of tropical storm Amelia. Amelia's climatic history was described in detail by Bowmar (1978, 1979, 1983) and the National Weather Service (1979). One of the most severe droughts in more than 20 yr was underway just prior to

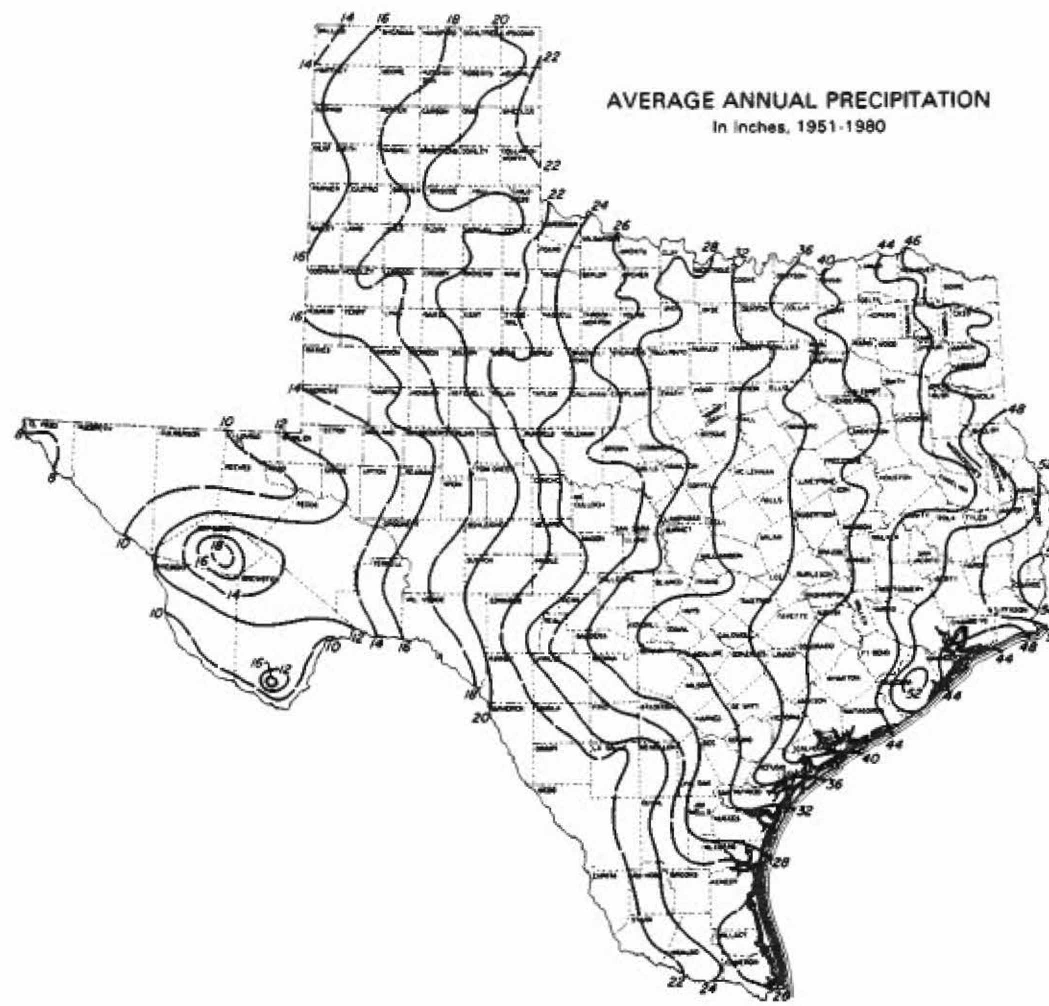


Figure 4. Mean annual precipitation in Texas. Note westward deflection of isohyet contours in Balcones Escarpment area, indicating increased rainfall relative to adjacent areas. From Larkin and Bowmar (1983, p. 18).

the advent of this storm. A subtropical ridge of high pressure had maintained dry conditions across much of the state throughout the summer. This ridg did not begin to deteriorate until the end of July when tropical storm Amelia formed in the Gulf of Mexico less than 50 mi off the southernmost Texas coast. Amelia was a minimal tropical storm (technically an "extratropical storm" because it originated north of the Tropics) when it made landfall in South Texas, causing little damage along the coast.

But as the storm moved northwestward, eventually crossing the Balcones Escarpment near San Antonio, it began producing extremely heavy rains. Amelia followed a path "virtually unique in Texas' weather" (Bowmar, 1979, p. 29). This slow-moving storm drifted over the escarpment and eastern Edwards Plateau, inundating small drainage basins. Rains exceeded 10 inches in 48 to 72 hr across a large area of Central Texas. The heaviest rains were those at the Manatt ranch near Medina, Bandera County, which set the U. S. 3-day rainfall record of more than 48 inches (Hansen, 1979) (fig. 2). Amelia remained a significant cyclonic system for six days following landfall, producing very intense rains all along its track into North-Central Texas.

Flooding associated with tropical storm Amelia w severe. Records of flood discharge in the Medina Rive basin are summarized above (under "Tropical Disturbances"). For a more complete discussion see Schroeder and others (1979), Sullivan (1983), and Bak (1984). Remarkable stage heights and discharge peaks were attained on the upper Guadalupe River, as well. Comfort, Kendall County, water level rose to nearly 41 breaking the previous record established in July, 1869 (Schroeder and others, 1979, p. 106). Drainage area this location is 838 mi^2 and peak discharge was 240,C cfs (table 1; fig. 3). Farther downstream, the U. S. Highway 281 bridge was flooded even though it stand ft above stream bed (Bowmar, 1983, p. 52). Near Sp Branch, Comal County, where the contributing drainag is 1,315 mi^2, stage height was greater than 45 ft. However, discharge in this reach had attenuated to 15 cfs (Schroeder and others, 1979, p. 107) (table 1; fig. Even this figure is phenomenal; 158,000 cfs is substar greater than mean discharge of the Nile at its mouth. the upper Guadalupe has only 1/1000th the Nile's watershed area. And yet, the Amelia flood was only third largest recorded at the Spring Branch station. highest stage, observed in 1869, was approximately 53

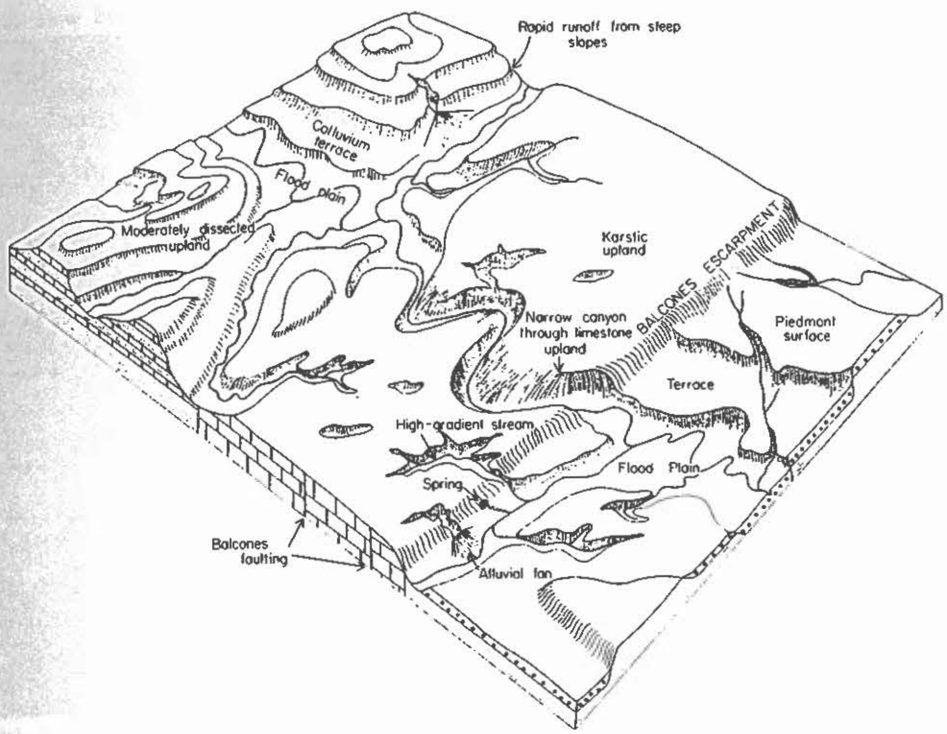


Figure 5. Block diagram representing geomorphic features that affect flood potential in the Balcones Escarpment area. From Baker (1975, fig. 3).

Damage resulting from the Amelia flood was enormous. In Central Texas, 25 persons were killed, 150 were injured, and 50 million dollars in property losses were sustained (Bowmar, 1979, p. 29). Another six persons were killed in North-Central Texas. All flood waters in the upper Guadalupe River watershed were contained by Canyon Lake reservoir in Comal County. Fortunately, lake level was low prior to the storm. Water storage increased by 226,200 acre-feet or approximately 74 billion gallons (Schroeder and others, 1979, p. 6). Areas downstream were not subjected to flooding but the lake afforded no protection of sites higher in the basin where rains were heaviest.

Geomorphic effects of the flood were pronounced. Devegetation, channel and flood-plain scour, large-scale deposition, modification of channel form, and temporary avulsion of meanders were common. Along both the Guadalupe and Medina Rivers, riparian woodlands including bald cypress trees six feet in diameter were scoured from miles of channel. Sullivan (1983, table 8) estimated 62 to 92 percent reduction of tree-crown cover in some reaches of the Medina. Van Auken and Ford (in preparation) will present a detailed account of effects of the Amelia flood on plant communities along the upper Guadalupe.

Baker (1977, p. 1069-1070) discussed the dynamic relationship between riparian vegetation and hydrologic characteristics of channels in flood. This discussion serves to illustrate effects of the Amelia flood on the upper Guadalupe River. Baker's model notes that dense stands of woody plants typically occupy the lower terraces, channel margins, and even the point bars of area streams. As water level begins to rise during a flood, the irregular floor of the low-flow channel is submerged. Boulders and bedrock outcrops that obstruct base flow are completely covered, which reduces resistance or channel roughness. With further increase in depth the stream, now "bankfull", overtops the sinuous low-flow channel, lowest terraces, and vegetated bars. Plants below the level of inundation increase roughness and tend to retard flow, but stream velocity actually increases in response to heightened discharge as the flood crest advances. Within the constricted bedrock channels common to this region, increased discharge is accommodated by rapid increase in stream depth. At this point, the mid-water zone of maximum velocity, the thalweg, shifts laterally inward across the slip-off bars, thereby increasing the effective channel radius and straightening the flood course around meanders.

Transition to the next phase of stream flow is governed by a critical threshold that in turn is dependent on the height and density of vegetation. If plants do not choke the flood channel, and if tree canopies remain above water there may be little additional damage. However, if canopies are submerged or flow is greatly restricted trees are uprooted, toppled, or sheared by the force of the water and impact of transported debris. Partial clearing of the channel reduces drag and increases local flow velocities. Rapid flow around remaining obstructions creates macroturbulence, causing intense scouring of gravel bars and low terraces at peak discharge. The coarsest sediment, including boulders and megaboulders, is transported only a short distance. Chute bars and gravel berms form at the downstream ends of bends on which scour was initiated. Valley-bottom scour is selective, partly because the combined resistance of the gravel fill and anchoring vegetation is variable. Following peak stage, as flow subsides, dragged and floated vegetation is deposited in the stream bed where it may inhibit waning discharge.

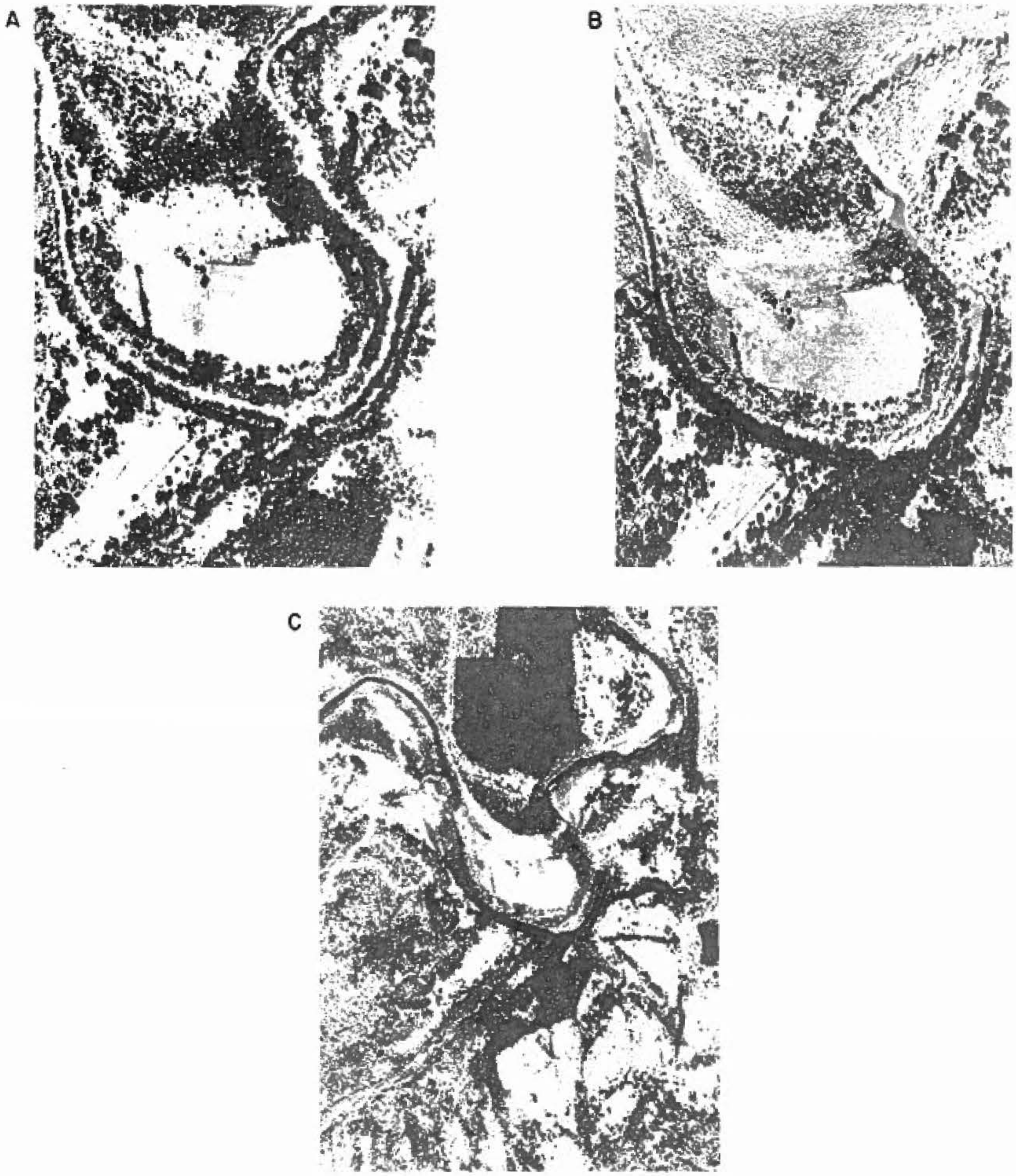


Figure 6. Aerial photographs of a meander bend of the upper Guadalupe River, Comal County. Tops of photos is north. Drainage is from west to east. Maximum east-west diameter of bend is approximately 2,250 ft. (A) U.S. Department of Agriculture, vertical black and white, BQU-1JJ-47, October 31, 1969. (B) General Land Office of Texas, vertical black and white, 1-2-114, November 29, 1978. (C) U.S. Department of Agriculture, vertical black and white, 40-48091-180-19.

A variation from Baker's model occurred in the Guadalupe basin approximately eight miles upstream from the U. S. Highway 281 bridge in western Comal County. Water depth in this area exceeded 50 ft. As predicted by the model, the thalweg shifted radially inward across the slip-off bar. However, this shift completely cut off the neck of the meander. Figure 6B shows scoured chutes, chute bars, large-scale gravel ripples, and aligned fallen trees at the cutoff. Peak flow bypassed this bend entirely. Consequently, this was one of the few reaches that sustained no serious loss of riparian vegetation such as large bald cypress and other trees. In fact, slack-water deposits began filling this channel segment at the same time contiguous areas were being scoured. A dam of fine sediment and plant debris temporarily blocked the mouth of Honey Creek, a tributary entering this bend from the south.

Effects of high-magnitude, low-frequency floods are much greater and more enduring in the bedrock-channel streams of Central Texas than in fine-grained alluvial channels of humid regions. Wolman and Miller (1960) have shown that, in stream systems of the latter type, relatively frequent low-magnitude events are most significant. In contrast, post-flood monitoring of Elm Creek (Comal County) and other streams in the Balcones Escarpment area indicate hydrologic characteristics typically are affected for years and perhaps decades (Baker, 1977).

A sequence of aerial photographs (fig. 6) shows the avulsed meander bend of the Guadalupe before, shortly after, and two years after the Amelia flood. Evidence of older (pre-1969) cutoffs at yet higher elevations attest to the episodic nature of these events (fig. 6A). Following the 1978 flood, the river occupied a deep, sharply-defined base-flow channel against the cutbank (fig. 6B). This channel cuts through gravel bars that in 1969 nearly blocked the river at several twists and tributary junctures. Coarse, open-work gravel deposits on slip-off slopes and low terraces show little evidence of reworking or revegetation between 1978 and 1980 (fig. 6C). Low adventitious plants such as grasses and forbs had completely covered the deep cutoff chute by 1980 but no large woody plants had been established. Trees that had fallen or been stranded at this meander bend in the 1978 flood were still in place in 1980. As of summer, 1986, changes in channel geometry and alignment and vegetation patterns that were effected in this reach by the Amelia flood had not been significantly modified.

Urban Flooding: Walnut Creek, 1981

Urban flooding generally is more complex than that in rural settings because it often results from failure or inadequacy of engineered drainage systems as well as excessive rains. A recent example of urban flooding in the Balcones Escarpment area is the "Memorial Day" flood of May 24 to 25, 1981, in Austin, Travis County (fig. 1). Bowmar (1981) presented a detailed review of the meteorologic causes of this flood. Late in the afternoon of May 24, warm moist air from the Gulf of Mexico was moving rapidly northwestward into Central Texas at middle levels of the atmosphere. Near-surface air had been heated throughout the day making the lower third of the atmosphere convectively unstable. Only 10,000 ft of additional vertical movement of surface air was needed to form significant thunderstorms.

An upper-level trough of low pressure moved through Central Texas early in the evening and provided the needed lift. Cloud tops reached 40,000 to 45,000 ft and remained in that range for more than 7 hr. Heavy rains began falling at about 9:30 p.m. Within a few hours, 8 to 10-inch rains had covered a large area of the city. The most intense rainfall and greatest total precipitation in the area were measured at stations in northern and northwestern Austin in the watersheds of Shoal and Walnut Creeks (Massey and others, 1982, fig. 6, table 2; Moore and others, 1982, figs. 2.2-2.4). One site near the headwaters of Walnut Creek recorded almost 6 inches of rain in one hour and 10 inches in 2 1/2 hours, which are intensities approaching the trend of worldwide precipitation maxima (fig. 2).

The effect of so much rainfall in a short period was severe flooding of parts of the city. Conditions were worsened by lighter but substantial rains of the day before which had saturated the ground (Moore and others, 1982, p. 4). A high percentage of impervious land cover is characteristic of urban areas and reduces further the potential soil infiltration. Under these circumstances, runoff was nearly complete. A remarkable aspect of the 1981 storm was the concentration of moisture in small, relatively stationary cells. Rains produced by these cells were highly localized within a widespread pattern of general though less intense rainfall. Small drainage basins were overwhelmed, producing massive flooding. Massey and others (1982) analyzed flood hydrographs and field observations and reconstructed areas of inundation along parts of Shoal, Little Walnut, and Walnut Creeks. The following discussion pertains to the headwaters of Walnut Creek, which were beyond the area covered by Massey and others.

Some of the most intense flooding resulting from this storm occurred in the uppermost reaches of Walnut Creek. The stream skirts well east of the Balcones Escarpment except in the upper part of the basin. There, tributaries drain off a segment of the escarpment which has subdued relief (fig. 7). These short but steep bedrock slopes enhance runoff onto adjacent Coastal Plain surfaces with low-permeability soils (Werchan and others, 1974). In addition, the small watersheds of these tributaries are areas of residential and small commercial development with 25 to perhaps 50 percent impervious cover (U.R.S./Forrest and Cotton and others, 1977, table 2-5). Each of these factors tends to amplify runoff.

Only a few years prior to the 1981 flood, upper Walnut Creek basin primarily comprised cultivated fields and rangeland. Until the late 1970's, the area was outside the corporate limits of Austin and other communities and therefore was not governed by construction codes sensitive to flood hazards. Earlier landowners evinced little voluntary concern; for example, initial construction had predated widespread recognition of risks inherent in development on flood plains. Railroads had been constructed along contours on high linear berms that obstruct movement of runoff. Rural roads with low narrow bridges, low-water crossings, and no storm culverts had been only partly replaced by urban streets and drains designed for 25 to 50-yr recurrence floods. Old and new roads and drainage ways were poorly integrated. Few of these problems had been corrected because urbanization was incomplete at the time of flooding. The area was a patchwork of modern urban streets, storm drains, housing, and businesses interspersed with undeveloped tracts, unimproved roads, and small industrial sites adjacent to streams. These conditions exaccerbated meteorologic and topographic factors associated with the flood of May, 1981.

Eight to ten inches of rain fell over most of the upper Walnut Creek drainage between 9:30 p.m. and midnight on May 24 (Massey and others, 1982, fig. 6, table 2). At FM Highway 1325 (Burnet Road), water level reached 19.5 ft, corresponding to 15,000 cfs discharge from a drainage area of 12.6 mi^2 (Massey and others, 1982, table 1) which approaches the nationwide trend line for high-discharge events (table 1; figs. 3, 7). Numerous homes and buildings were damaged by rising water along the channel or unchanneled flow on nearby slopes. At Waters Park Road just upstream from Burnet Road, a few commercial buildings on the flood plain were completely destroyed or badly damaged. One small manufacturing plant was submerged by more than 15 ft of very rapidly moving water. This high-velocity macroturbulent flow transported heavy industrial equipment, large commercial trucks, and passenger cars more than one mile downstream from the plant site (figs. 8A, 9). To accomplish this the stream carried some of its load over a 15-ft high railroad trestle partly blocking the channel just downstream.

An unnamed tributary of Walnut Creek that has a drainage area of approximately 2.5 mi^2 probably was entirely within one of the zones of 10-inch rainfall depicted by Massey and others (1982, fig. 6). Only part of this drainage area contributed to a reach where flood waters damaged a bridge and washed out a railroad berm along Dorsett Road (fig. 7, 8B). Just downstream, a woman was killed when her automobile was submerged at a newly constructed bridge on Duval Road (Massey and others, 1982, p. 22; fig. 3.1 of Massey and others is in error). Twelve additional fatalities occurred along other streams which also destroyed homes and businesses.

CATASTROPHIC DAM FAILURE: AUSTIN, 1900

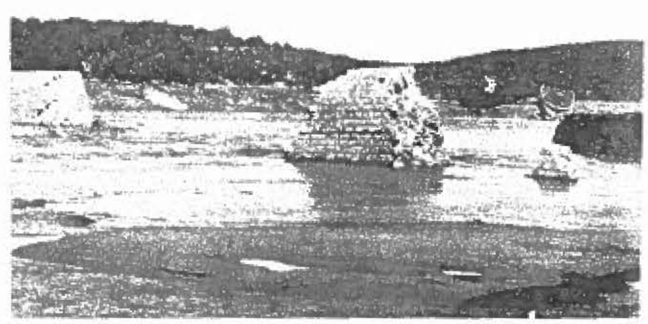
Floods have posed serious hazards throughout the history of Central Texas. In an effort to control flooding and harness the Colorado River for water supplies, recreation, and hydroelectric power generation, the city of Austin and, later, the Lower Colorado River Authority constructed and maintained a dam in western Austin. The present structure, known as Tom Miller Dam, impounds Lake Austin. An earlier dam at this site was the world's largest masonry structure when it was completed in 1893 (Lower Colorado River Authority, undated). The reservoir formed by this early dam was called Lake McDonald (fig. 10A). Design problems and controversy surrounding the advisablity of the site raised some concern although the dam appeared stable (Taylor, 1930, p. 25). But on April 7, 1900, a major flood in the Colorado watershed caused the dam to fail, draining Lake McDonald. Sections of the dam were displaced downstream yet remained upright (fig. 10B). Other sections were washed away entirely. The dam was reconstructed, only to fail a second time in 1915 (Lower Colorado River Authority, undated). Further construction was delayed. Another flood in 1935 did additional damage (fig. 10C). Finally, in 1938, the existing structure was completed and has operated with few interruptions since that time.

CONCLUSIONS

The Balcones Escarpment area is one of the most flood-prone regions of the world. Intense rainstorms occur in the area with surprising frequency. Physiographic factors produce rapid runoff which results in phenomenal stream discharge. Urbanization reinforces these natural conditions and increases the probability of casualties and property losses. Numerous flood-control structures throughout the region provide some measure of security but heavy rains are so localized that catastrophic floods may occur almost anywhere else in the drainage basi.. Small, completely unregulated streams may undergo enormous increases in discharge, posing a considerable threat particularly in urban settings. Within the Balcones Escarpment area, the distribution of major flood-producing storms in time and space is random. Therefore, the only completely effective approach to flood protection is avoidance of geomorphically-defined flood plains and channels.

A

B



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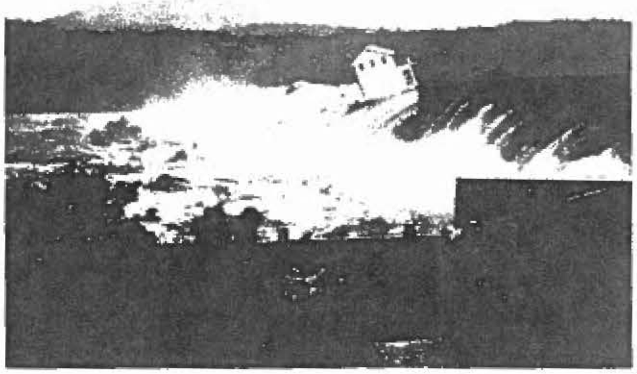

Figure 10. Historic photographs of Austin Dam (now calle Tom Miller Dam). Photos courtesy of Austin History Center. In all photos drainage is from north to south. (A) Photo number Chal 8484. Dam soon after construct (photo taken about 1895). View is toward east. Note paddlewheel steamboat Ben Hur at left. (B) Photo numl Chal 1613. Remnants of dam soon after flood of Augusi 7, 1900 (photo taken about 1900). View is toward northwest. Section in center has been displaced downstream. Note wreak of Ben Hur at right. (C) Pho number Chal 65. Dam during flood of June 15, 1935. View is toward west.

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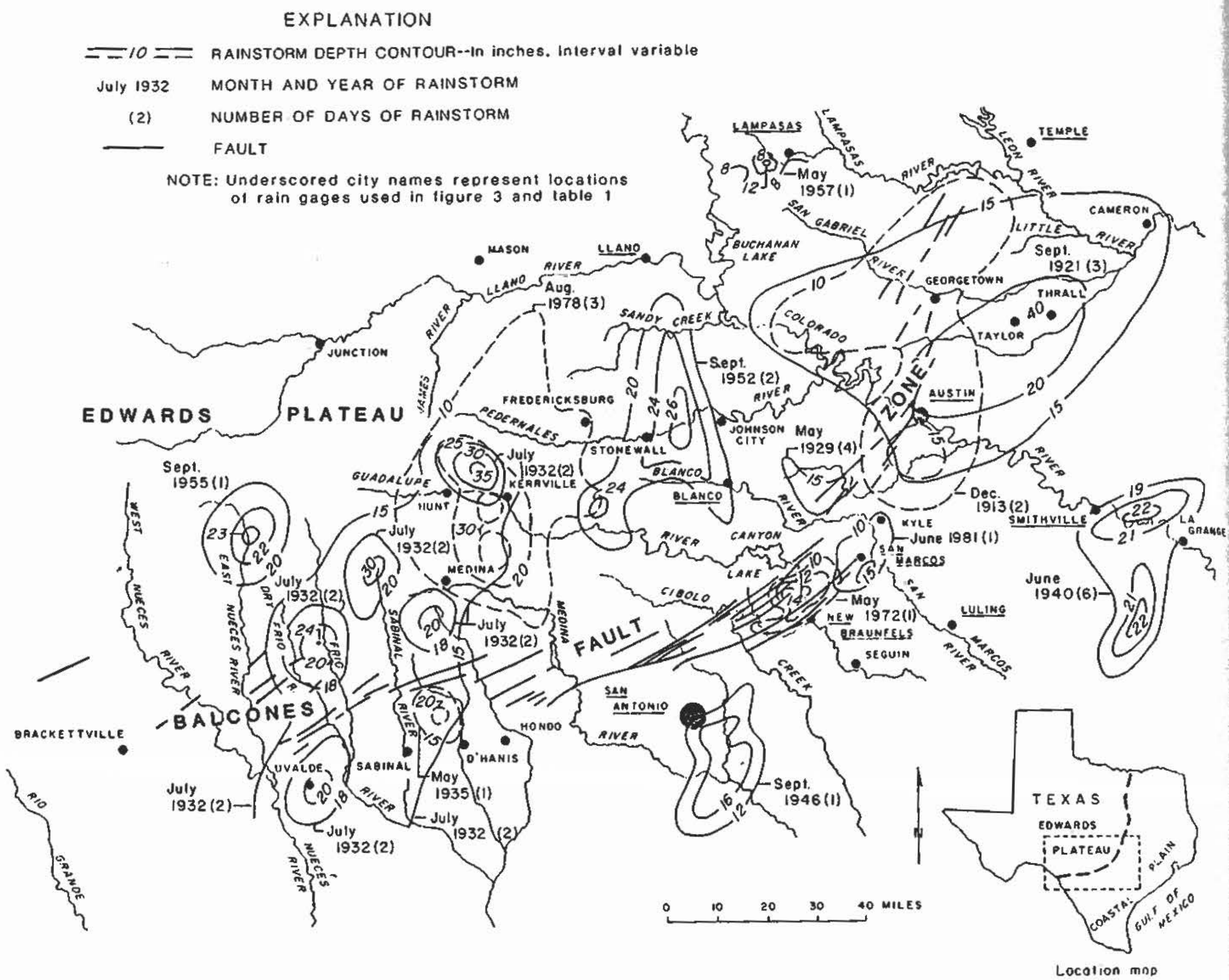


Figure 1.--Locations, dates, and depths for selected large rainstorms in central Texas.

Modified from Baker (1977)

inches of rain in 12 hours, and 38.2 inches in 24 hours--the greatest known depths of these durations to occur in the continental United States. The storm of May 31, 1935 produced 22 inches of rainfall in 2 hours 45 minutes near D'Hanis--also a record rate for that duration.

CHARACTERISTICS OF STORMS

The characteristics of many large storms in Central Texas, however, are unknown due to lack of documentation. Almost all storm documentation is from rain gages, most of which are operated by the National Weather Service. The areal and temporal coverage of these gages, as well as the type of data being collected are inadequate to properly document many of the large storms. In many areas, distances between rain gages are greater than 40 miles--gaging density is as low as one gage per 1,000 square miles. Also, many of the gages have only short periods of record--many less than 10 years. Another gaging problem occurs because most of the gages in Central Texas are non-recording collectors of rainfall. At those gages, rainfall depths are measured once per day by observers, thus only daily rainfall values are available. Storm intensities are available only for those few gages which record incremental rainfall. Because of these facts, the greatest depths and intensities for many storms are not recorded, and many storms are totally undocumented. Lack of a complete data base contributes to the lack of information concerning the recurrence of large rainstorms.

Another problem in predicting large storms is caused by large areal ranges in the depths of the greatest storms,and large differences between the largest storm depths at individual sites. The rainfall records for many rain gages in Central Texas are analyzed to demonstrate these characteristics. Ten gages operated by the National Weather Service with long-term data are chosen for the analyses. The mean-annual precipitation for those sites, which are shown in Figure 1, range from about 26 to about 36 inches. With the exception of the Smithville gage, all the gages were installed before 1900. A common period of 1900-84 is chosen for the analysis.

The values of the greatest daily rainfalls for

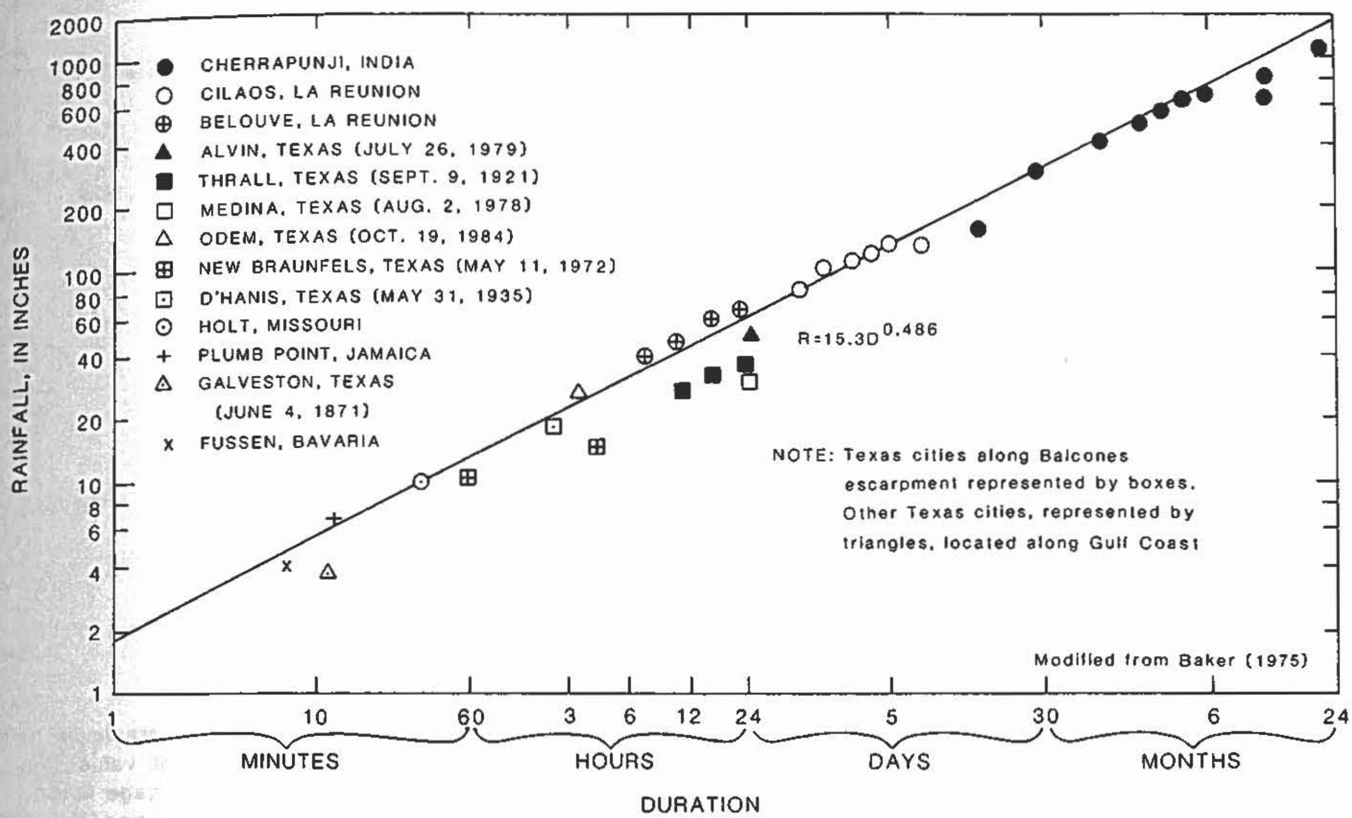
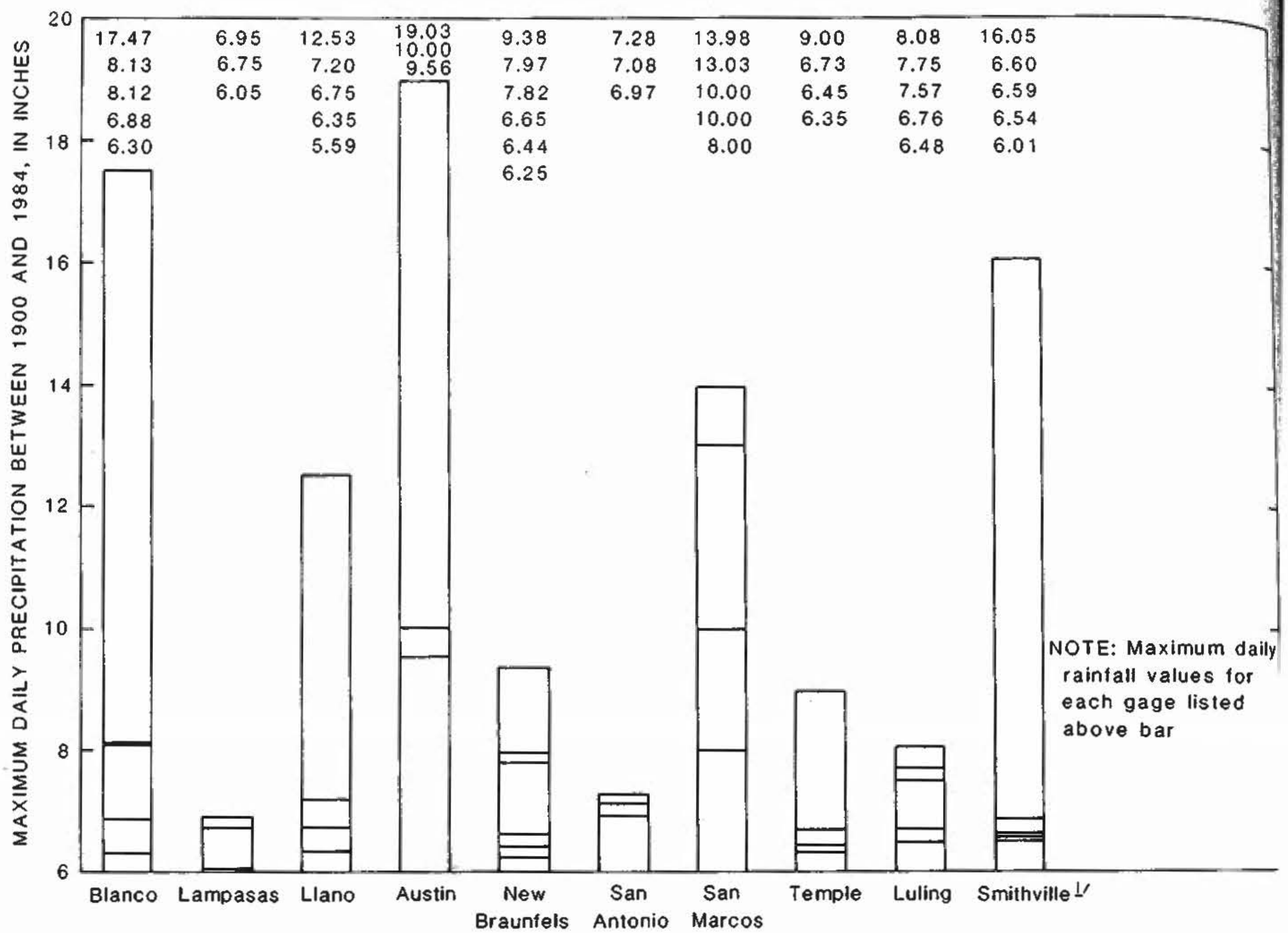


Figure 2.--Magnitude-duration relationships for selected largest rainfalls of the world and of Texas.

each of the gages are shown by bar graphs in figure 3. The horizontal lines in each bar represent the depths of the highest 3-6 daily values for each of the gages during the period 1900-84. These values are listed at the top of each bar. These data illustrate the range in the highest daily rainfall values between gages in Central Texas. The maximum-daily rainfall for 2 of the gages is less than 7.5 inches while 3 of the gages have had daily rainfalls greater than 15 inches. Figure 3 also shows the large differences between the largest storms at individual sites. For example, the highest daily value at the Smithville gage is 16.05 inches, while the second through fifth highest values are between 6.60 and 6.01 inches. Incremental rainfalls can vary as significantly as the daily rainfalls. These variations and inconsistencies in rainfall illustrate the difficult in predicting rainfall magnitude and intensity at specific sites.

Large storms are also unevenly distributed in time throughout sites in Central Texas. Table 1 shows, for five-year periods, the number of months for which the monthly rainfall for each gage exceeded 10 inches. The irregular frequency at which large storms occur at each gage is indicated in the table. For example, at the Austin gage, 12 of the 19 months which exceeded 10 inches of rainfall occurred during the first 30 years of the 85-year period. The Austin gage, installed in 1856, represents the first rainfall gage in Central Texas. The data for that gage demonstrate that the large storms can be irregular or "clustered" in time. For example, 11 of the 12 "wettest" months on record occur before 1930. A rain gage that records incremental rainfall was installed in Austin in about 1928. Rainfall frequency-duration statistics, based on values from the gage, are used throughout the area as the basis for flood-plain delineations and designs for urbanization. It is likely, however, that these data are not representative of the "wet" period occurring before 1930. In Austin's case, the 130 years of rainfall data indicate that the first half of the period had many more large storms and greater storm depths than the second half of the record. The largest storms for the other gages also are temporally clustered--a problem which can bias statistical studies of the depths and frequencies of large rainstorms.

The most common method used to predict design rainfalls can be inadequate because of the areal and temporal characteristics of these storms. Rainfall frequency-duration statistics are commonly used by governing officials as the basis for delineating flood plains, and for designing urban developments. Generally, rainfall statistics for a community are based on one raingage in the area. Standard statistical methods for rainfall prediction assumes the recorded depths or intensities to be linearly related to frequency of occurrence. This method of prediction cannot account for the large ranges in depths of the largest storms at the site, or temporal clustering, both of which may bias the statistics.



1/Smithville gage installed in 1918

Data from Douglas Fenn, National Weather Service, oral communication, 1986, and George Bomar, Texas Water Commission, written communication, 1986

Figure 3.--Maximum daily precipitation values, 1900-84.

SUMMARY

In summary, areal and temporal documentation of large storms is hindered by lack of appropriate gaging. Also, large ranges occur areally in depths of the largest storms. At individual sites, large differences between the depths of the largest storms occur, along with temporal clustering of the large storms. These characteristics present problems in planning and managing land and water resources. Regional studies of the magnitudes, frequency, and locations of large storms would probably be very beneficial in developing methods for better predict these occurrences. If all relevant climatic, physio graphic, and rainfall data and information were gathered, analyzed, and interpreted, better planning and managing may reduce the threat to life and property caused by rainstorms.

Table 1. Number of months for which monthly precipitation exceeds 10 inches, 1900-1984

Period of precipitation	Gages west of Balcones escarpment			Gages located on Balcones escarpment					Gages east of Balcones escarpment	
	Blanco	Lampasas	Llano	Austin	New Braunfels	San Antonio	San Marcos	Temple	Luling	1/Smithville
1900-04	1			3	1		3	4	2	-
1905-09			1				1	1		-
1910-14	1	1		2	1		2	1	1	-
1915-19				3	1	1	1		1	-
1920-24		1		2	1		2	2		
1925-29	1			2	1		2	1	1	3
1930-34			1					2		
1935-39	2	3	4		1	1	1		1	4
1940-44	3	3		1	1		2	1	2	3
1945-49	1				2	2				
1950-54	1		1				1			
1955-59	1	1			1	1	1	2	2	1
1960-64	2			2			1		1	2
1965-69	2					1		2	1	
1970-74	2	1	1	1	4	4	1		3	1
1975-79			1	1	1		2		2	
1980-84	1			2	1		1	1	1	1
Total number of months	18	10	9	19	16	10	21	17	18	15

1/ Smithville gage installed in 1918

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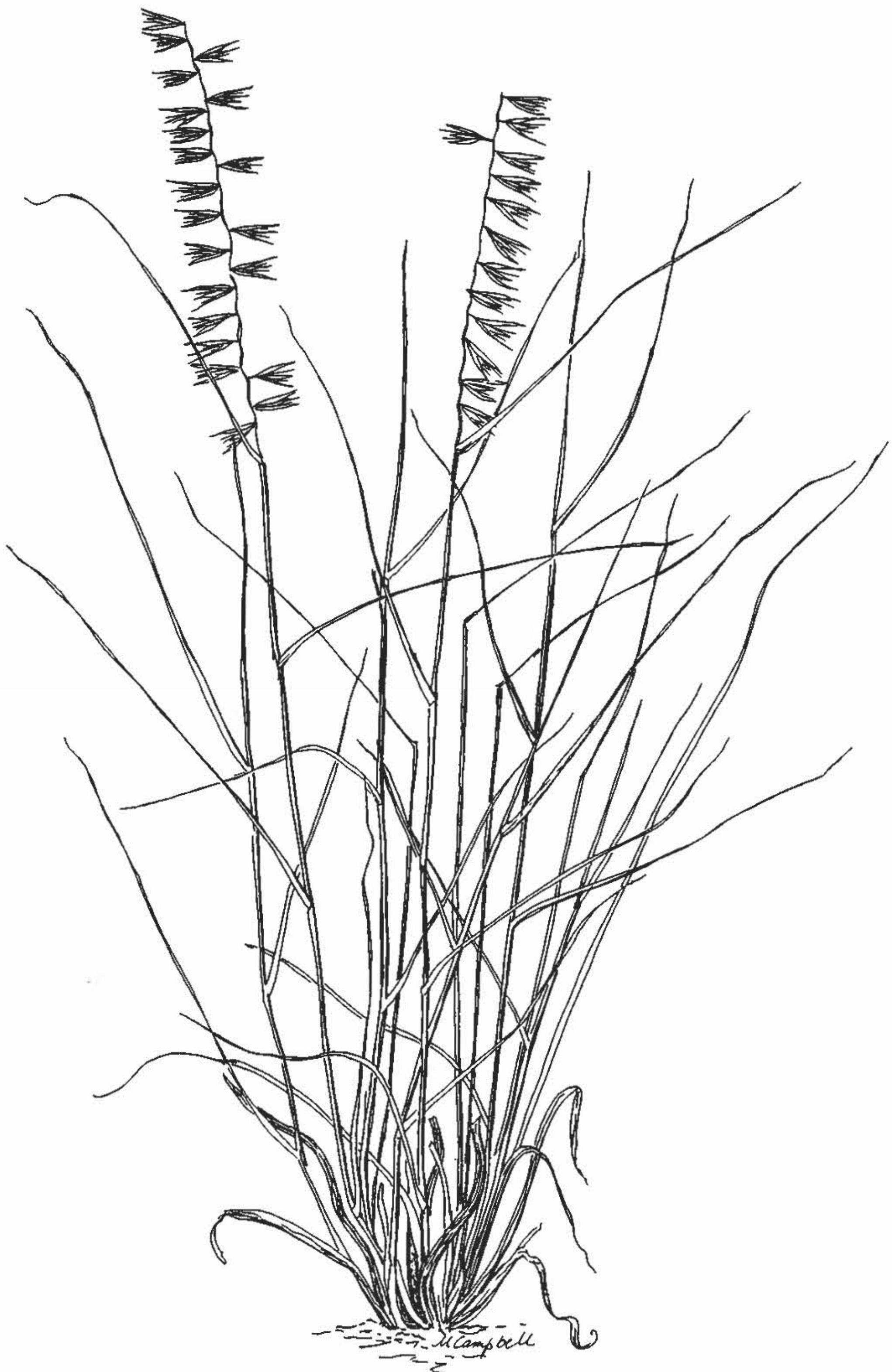

Boutelou<u>a</u> curtipendula
Side oats grama
State grass of Texas

PLANT COMMUNITIES OF THE EDWARDS PLATEAU OF TEXAS: AN OVERVIEW EMPHASIZING THE BALCONES ESCARPMENT ZONE BETWEEN SAN ANTONIO AND AUSTIN WITH SPECIAL ATTENTION TO LANDSCAPE CONTRASTS AND NATURAL DIVERSITY

DAVID H. RISKIND
TEXAS PARKS AND WILDLIFE DEPARTMENT
4200 Smith School Road
Austin, Texas 78744

DAVID D. DIAMOND
TEXAS NATURAL HERITAGE PROGRAM
General Land Office
Stephen F. Austin Building
1700 North Congress Avenue
Austin, Texas 78701

INTRODUCTION

The Edwards Plateau of west central Texas comprises about 93,240 sq. km. of territory (LBJ School of Public Affairs 1978). It contains several distinct subregions. It is species rich and its mesic canyons harbor a number of endemic and insular species (Amos and Rowell 1984). Although dominantly limestone, the southern margin of the Plateau is bounded by the Balcones fault system with limestone, chalk, marl, claystone, and localized outcrops of intrusive igneous features (Lonsdale 1927). Hence, the Edwards Plateau is a large distinct region that supports a diversity of habitats. The following sections will provide a description of the variation in physiography, geology, climate, soils, and vegetation that compose the Edwards Plateau; but emphasis will be on the landscape lying between San Antonio and Austin.

Physiography and Topography

Hill (1892) was the first to recognize the Edwards Plateau as a distinct physiographic province, but the definition of its extent has varied. Tharp (1939) described the vegetation of Texas and included the Grand Prairie to the north and Hill Country to the south and southeast in his definition of the Plateau, but excluded the Central Mineral Region (= Llano Uplift) and the flatter, central and northwestern portions. Dice (1943) provided a map of biotic provinces of North America based primarily on faunal distributions, and included the Plateau with the Rolling Plains in his Commanchean Biotic Province. This treatment was later modified by Blair (1950), who separated the Plateau (including the Llano Uplift) as the Balconian Province. Gould (1975) included the Llano Uplift and Stockton Plateau west of the Pecos River, but not the Lampasas Cut Plain in a widely recognized treatment of the vegetational areas of Texas. Godfrey, et al. (1973) also used a similar definition, but excluded the Llano Uplift. The Lyndon B. Johnson School of Public Affairs (1978) published a map of the natural regions of Texas which was essentially similar to one adopted by the United States Fish and Wildlife Service (1979). These treatments excluded the Llano Uplift but included the Lampasas Cut Plain in the Edwards Plateau natural region.

The Edwards Plateau, taken in broad context, is a southern extension of the Great Plains of North America (Fenneman 1931, Hunt 1974). To the south and east it is separated from the lower-lying West Gulf Coastal Plain by the Balcones Fault Zone, where elevations drop sharply to less than 180 m. To the north it grades gradually into the Rolling Plains, while to the northwest it grades into the High Plains (= South Sandy Plains). To the west it is separated from the Stockton Plateau by the Pecos-Devils River divide. The Stockton Plateau is geologically similar to, and has been considered by some as part of the Edwards Plateau (Gould 1975); however, it has more often been lumped with the more desertic Trans-Pecos region (Tharp 1939, LBJ School of Public Affairs 1978). Figure 1 provides a schematic rendering of this physiographic region.

The elevation of the Edwards Plateau generally increases from the southern and eastern margins to the northwest. Austin and San Antonio on the south are at 167 m and 213 m, respectively, while Junction near the center of the Plateau is at 521 m and Big Lake on the northwest is at 734 m.

The southern and southeastern margins of the Edwards Plateau are highly dissected, and could hardly be considered a plateau. This "Hill Country" (= Balcones Canyonlands) consists of steep canyons, narrow divides and high gradient drainages. These short streams originate in the Hill Country and generally flow south or southeast to the Gulf of Mexico. They include, from west to east, the Nueces, Frio, Sabinal, Medina, Guadalupe and Blanco Rivers. The Pedernales flows eastward through the region, joining the Colorado just west of Austin (Fig. 2). There are numerous springs in this region at the edge of the upthrust area of the Balcones Scarp. These springs are important water sources of cities situated along the boundary of the Edwards Plateau (= Great Plains physiographic province) and the West Gulf Coastal Plain physiographic province.

The granitic Central Mineral region or Llano Uplift centered in Llano, Mason and Burnet counties is likewise not a plateau; but topographically, it is a basin with respect to the main body of the Plateau to the south and west. Its geologic origins are as an uplift; hence, the name. There are numerous rounded, nearly barren granitic outcrops and the landscape is gently rolling except near drainages such as the Llano and Colorado Rivers and their tributaries or near granite outcrops, where steep slopes and some sheer cliffs appear.

The Lampasas Cut Plain on the northeast is generally flatter than the Llano region or southeastern margins of the Plateau previously discussed. It consists of broad valleys and wide stream divides with relatively few steep, high gradient canyons. The Lampasas and San Gabriel Rivers are the only two major streams that bisect the area.

in Abbott, Patrick L. and Woodruff, C.M., Jr., eds., 1986, **The Balcones Escarpment, Central Texas**: Geological Society of America, p. 21-32

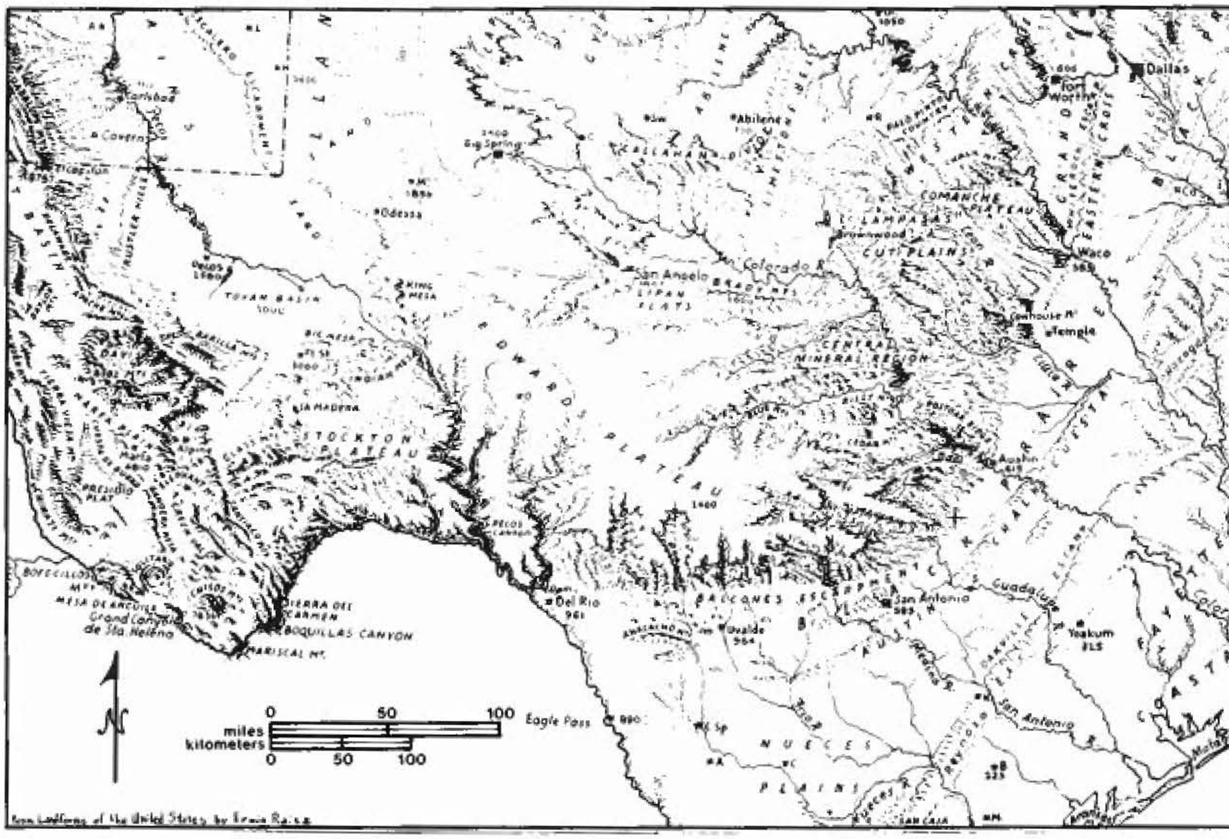

Figure 1. Landforms of the Edwards Plateau and adjacent areas.

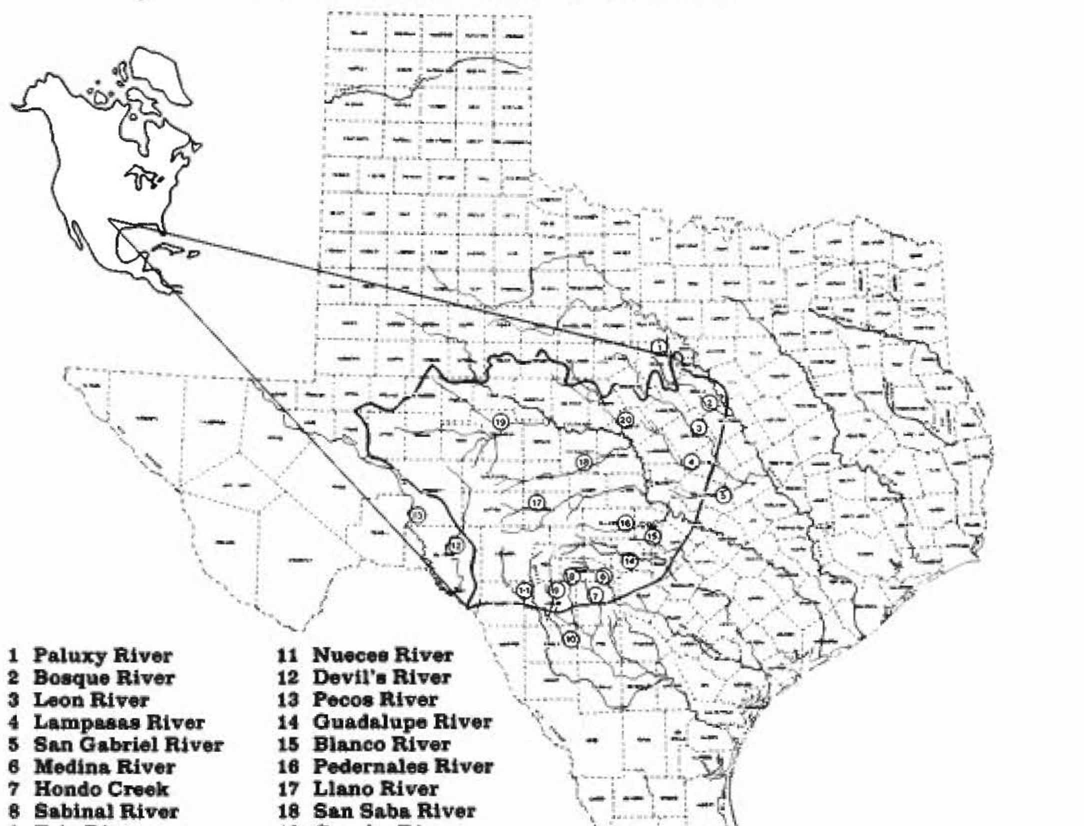

Figure 2. Approximate delineation of the Edwards Plateau natural region showing major drainages.

From the central Edwards Plateau to the north and northwest the topography is generally flat to gently rolling with rounded hills, wide stream divides and few steep slopes. Much of the area could be described as a broad plain. Several major streams cut west to east paths across this plain, including, from north to south, the Concho, San Saba and Llano Rivers. These eventually join the Colorado, which flows southerly through the Llano Uplift and eventually to the Gulf of Mexico. The Devils River and its tributaries also bisect this plain in the southwest but flow south to join the Rio Grande.

Geology

Most of the Edwards Plateau consists of limestone rock of Cretaceous origin. The less eroded central and western portions are dominated by Lower Cretaceous rocks within the Edwards Limestone group, while southward and eastward Edwards Limestone has largely been eroded exposing older Cretaceous material, primarily the Glen Rose formation (Sellards et al. 1932). The Lampasas Cut Plain, which represents a generally more mature landscape than the main portion of the Edwards Plateau to the south and west, is composed of strata from both the Glen Rose and Fredericksburg Divisions. Patches of limestone, dolomite, chert and marl alternately crop out at the surface across the area. Some Upper Cretaceous material, consisting primarily of chalk and marl, crops out along the southern and western margins of the Plateau.

The geology of the Central Mineral Region or Llano uplift is strikingly different from that of the remainder of the Edwards Plateau. It is an intrusive outcrop of Precambrian rock which comprises about 1.5 million ha in the northwestern part of the Plateau. The material overlying this intrusive granite, where it has not been eroded away (around the perimeter, especially the northern border), consists of early Paleozoic sedimentary rocks including limestone, dolomite, sandstone, siltstone and shale. Minerology of the granitic material varies, with hornblende schist, graphite schist, quartz-feldspar gneiss and quartz-plagioclase-microcline rock common. In addition, local Precambrian outcrops are scattered throughout the southern and eastern margins of the Plateau.

Soils

Variation in substrate and a generally hilly landscape have led to the development of a large number of different soil types on the Edwards Plateau. Excluding the Llano Uplift, upland soils of the Plateau have generally developed in place and occur over limestone or caliche. They are shallow and rocky or gravelly on slopes and deep in broad valleys and on flats. Most are dark colored and calcareous, although pH is variable depending on base saturation of the substrate, and the degree of soil profile development (Godfrey et al. 1973). Surface texture also varies from loamy to clayey, depending on substrate and profile development.

These upland soils are generally classified as Mollisols on flats and valleys (deeper soils) or Inceptisols on slopes (shallow soils). Many have vertic properties due to montmorillonitic clay minerology. These soils shrink and swell on wetting and drying, developing deep cracks in the dry months. Clayey Vertisols are also present, especially in the east or run-on areas in the north and northwest. Both Mollisols and Vertisols have surface layers that are high in organic matter, but nitrogen, phosphorus, potassium, iron and magnesium may still be limiting factors to plant growth when water is sufficient. Inceptisols may also have fairly high organic matter content, although they are not generally as fertile, mature, or deep as Mollisols and Vertisols. Over less alkaline parent materials or where soil profile development has occurred for long periods over moderately or non-calcareous secondary colluvium or alluvium (for example, on old stream terraces or in former shallow depressions), loamy Alfisols have developed. They are often less fertile than Mollisols or Vertisols, although plant-soil water relations may be good.

Soils of the Llano Uplift have generally developed over long periods from granitic materials or, around the margins of the region, from a variety of shale, limestone, dolomite or siltstone. Most have acid, loamy surface layers and are classified as Alfisols. Some deep, well-watered, sandy deposits occur around the base of major granite outcrops and in stream bottoms. These have poor profile development and are classified as Inceptisols.

Climate

The climate of the Edwards Plateau becomes increasingly arid to the west and cooler to the north. The eastern and central portion is classified as sub-tropical, subhumid, while the western one-fourth is classified as sub-tropical, semi-arid (Larkin and Bomar 1983; Fig. 2). These categories correspond to Thornthwait's (1948) dry sub-tropical and semi-arid moisture regions. The general decrease in moisture content of Gulf air as it flows northwestward across the Plateau is the controlling factor responsible for this difference in moisture regime.

Mean annual precipitation decreases from east to west, ranging from about 85 cm/yr on the eastern edge to 35 cm/yr on the western edge of the Plateau (Table 1); (Bomar 1983). There is a concomitant increase in mean lake surface evaporation rates from east to west. July plus August evaporation rates increase from 46 cm in the east to 57 cm in the west, while annual rates increase from 160 cm/yr to 206 cm/yr from east to west. The July plus August precipitation rates also decrease from east to west, ranging from 13 cm to 9 cm (Larkin and Bomar 1983). Hence, there is a pronounced decrease in summer precipitation and an increase in summer evapotranspiration, and this effect is increasingly severe to the west. In addition, there are periodic drought years, such as those that occurred in the mid-1950's and in 1980 that cause even more severe moisture stress on plants.

The average frost-free period ranges from approximately 260 days in the south (early March through late November) to 230 days in the north. Summer average highs and lows do not vary significantly across the Plateau and average about 35°C and 22°C respectively. Average January lows decrease northward, ranging from approximately 4°C to 0°C. Hence, there is little variation in environment related to north-south variation in temperature.

Along with normal summer moisture deficiencies and periodic severe drought, high intensity rainfall events caused by tropical cyclonic disturbances are characteristic of the Edwards Plateau. These torrential storms are most common in the Hill Country along the southern and southwestern margins of the region (Baker 1975). Flooding and erosion caused by the storms are major factors in the environment of the Edwards Plateau.

Table 1. Normal annual and growing season (April-October) precipitation based on 1951-1980 means, for stations along a east to west transect across the central Edward's Plateau.

	PRECIPITATION (cm)	
STATION	ANNUAL	GROWING SEASON
Austin	80.0	54.5
Fredricksburg	72.8	54.6
San Antonio, TX	69.96	56.80
Junction	57.2	41.5
Ozona	46.3	37.2

VEGETATION

The climate of the Edwards Plateau becomes markedly drier to the west, and the topography becomes less dissected. Soils of the Llano Uplift region are generally sandy and non-calcareous, in contrast to the calcareous, clayey or loamy soils of most of the remainder of the region. The southern and southwestern margins (= Hill Country; Balcones Canyonlands) are markedly more dissected, and the topography rougher than that of the Lampasas Cut Plain on the northwest. These observations have been made by early (Bray 1906, Johnson 1931, Tharp 1939, 1952) as well as later (LBJ School of Public Affairs 1978, USFWS 1979) investigators, who have all separated these regions into separate vegetational or at least physiographic subregions. A recent map of the current vegetation of Texas based on LANDSAT data (McMahan et al. 1984) and a map of potential natural vegetation by Kuchler (1964) have noted the differences among these regions. The Balcones Canyonlands or Hill Country region is more mesic and supports more forest or woodland vegetation on slopes and in canyons; the Lampasas Cut Plain is also mesic but flatter and more open and, therefore, grassier; the central and western Plateau becomes more xeric and more open; and the Llano Uplift region contains a species composition similar to but distinct from the remainder of the Plateau. Hence, the interaction of climate, topography and soils cause major shifts in vegetation patterns evident across the region.

These factors, along with past and present disturbance regimes, also interact to cause coarse and fine scale variations in vegetation on the Plateau. The demise of free-roaming bison, introduction of domestic livestock and exotic herbivores and the drastic change in fire regime since 1700 have led to widespread increase in density of woody species and loss of grasslands across the Plateau (see Smeins 1980). In addition, variations in the timing and density of grazing by domestic livestock together with mechanical and chemical brush control have led to an even more patchy landscape in which the influence of natural variation in soils, slopes and aspect are obscured.

The following will provide a general regional characterization of the contemporary and potential late seral vegetation of the Plateau; however, the principal focus will be on the San Antonio-Austin segment of the Balcones Canyonlands and adjacent lands east of the fault zone, including the southern extension of the Blackland Prairies.

Affinities of the Vegetation

Modern flora and fauna of the Edwards Plateau are comparatively well known. Pleistocene fauna, known primarily from caverns and sinkholes is likewise fairly well known (Lundelius 1967); however, we know almost nothing of the last 22,000 years of vegetational history on the Plateau except through inference from Quaternary pollen records to the east and west (Bryant and Schafer 1977).

There are hints of an exciting complex vegetational history which is manifested in the modern occurrence of certain insular woodland communities such as the temperate deciduous Acer-Tilla-Quercus or evergreen Pisatacia-Quercus or Lacey oak (Quercus glaucoides), woodlands restricted to mesic canyons; the restricted, insular Pinus remota evergreen pygmy woodlands; the insular Taxodium-Sabal grotto swamps; the tropical ferns in isolated sinkholes, and too, from such exciting stories as the apparently rapid colonization of Ashe juniper (Juniperus ashei) onto the Plateau from a source on the margins of the Mexican Plateau (Adams 1977).

Plant communities of the more mesic, dissected portions of the Plateau owe much of their origin to the Sierra Madre Oriental and its outliers. One could also characterize the Balcones Canyonlands of the Plateau as northern facies of the eastern piedmont of the Sierra Madre Oriental. Mesic habitats in the protected eastern canyons are strongly influenced by floristic contributions from the eastern (Austroriparian) deciduous forests, including tall grass prairie species.

The Plateau on the undissected uplands owes much of its influence to the Great Plains grasslands to the north. On the more xeric western plateau and its canyons, the biotic contribution is from the dry plateaus and massifs of northern Mexico and Trans-Pecos Texas where semidesert grasslands prevail. To the northwest, centered in Reagan, Irion, Schleicher and Crockett Counties, the mesquite-tobosa community seems more akin to the Rolling Plains, as does the mesquite savannah on heavy textured soils of the Llano Basin.

Other parts of the Llano Basin, over lighter textured soils, are covered in an open oak-hickory woodland whose affinities are with the Cross Timbers and oak woodlands to the north and east. Oak woodlands are also widespread on limestone uplands across interfluvial divides on the eastern margins of the Plateau where Alfisols occur, usually over karstic features or Quaternary terrace deposits.

The southern segment of our treatment area, near San Antonio and environs, is influenced by yet another suite of elements whose origins are the Tamaulipan thorn woodlands/shrub of the Mexican Gulf

Coastal Plain. Taxa such as spiny hackberry (Celtis pallida), catclaw acacia (Acacia gregii), fern acacia (A. berlandieri), persimmon (Diospyros texana) and mesquite (Prosopis glandulosa) tend to be more common on dry, edaphic sites or where disturbance has played a role in landscape development. Disclimax or disturbed grasslands on heavy soil usually have an abundance of huisache (Acacia smallii), while a sub-tropical component, anaqua (Ehretia anacua), is found occasionally along riparian corridors.

Balcones Canyonlands

This region of steep slopes and high gradient streams is dominated by evergreen woodlands and deciduous forests. Grasslands are restricted primarily to drainage divides; usually in the context of open woodlands. Although more quantitative data on plant ecology are available for this region than for other subdivisions of the Plateau (Buechner 1944; Solcher 1927; Lynch 1962, 1971; Van Auken et al. 1979, 1980, 1981; Ford and Van Auken 1982; Bush and Van Auken 1984, 1985; Fowler 1985: Van Auken and Bush 1985; Fowler and Dunlap 1986) the composition and structure of the plant communities of this zone are still not well known. Community composition reflects exposure, edaphic factors and microclimate, and although vegetation changes covered by the factors are qualitatively obvious, only one study (Van Auken et al. 1981) has investigated this topic for the Escarpment, and none have compared communities of similar habitats across moisture and exposure gradients in the zone. An idealized profile of the canyons contains at least three major community types.

Streamsides

Along perennial watercourses, the streamside component is dominated in our area south of the Colorado by bald cypress (Taxodium disticum), sycamore (Platanus occidentalis) and to a lesser extent black willow (Salax nigra). Buttonbush (Cepalanthus occidentalis) is often conspicuous in the shrub stratum. Quite often, bald cypress forms monodominant stands. This streamside community is always very narrow, often less than 2 m. Dwarf Palmetto (Sabal minor) occurs occasionally. This community is a western expression of eastern swamp communities, although it is adapted to periodic flooding of great magnitude, which may be essential for its maintenance (see Gehlbach 1981). Cypress swamps are well expressed at grotto sites like Hamilton's Pool and West Cave Preserve (Travis County) and at Honey Creek and Curry Creek in Comal County.

Intermittent drainages support sycamore woodlands or in the case of very "dry" sites, cedar elm usually predominates. If deep soils accumulate, the streamside component is often indistinguishable from some mesic lower slope or floodplain woodlands within canyonlands.

Floodplains

Like the streamside community, floodplains are subject to periodic catastrophic flooding, and are dominated by some combination of oak-elm-hackberry gallery forests. In our area this gallery woodland also may include Arizona walnut (Juglans major), box elder (Acer negundo), chittamwood (Bumilia lanuginosa), soapberry (Sapindus), Ashe juniper, pecan (Carya illinoensis), eastern cottonwood (Populus deltoides), live oak, Texas oak, chinkapin oak (Quercus muhlenbergii), ash (Franixus pennsylvanica), American elm (Ulmus americana), cedar elm, (Q. sinuata), red mulberry (Morus rubra), and rarely basswood (Tilia caroliniana), although there is considerable east to west variation (Buechner 1944, Ford and Van Auken 1982). Species such as pecan, scalybark oak, chinkapin oak, and black walnut are more important in the east or on more mesic bottoms. Live oak, cedar elm, and sugarberry increase to the west or on more xeric bottomland sites. Floodplain forests are usually at least two-layered, with deciduous holly (Ilex decidua), roughleaf dogwood (Cornus drummondii), elderberry (Sambucus spp.), Mexican plum (Prunus mexicana), and hoptree (Ptelea trifoliata) often present. Sugarberry and cedar elm increase in disturbed floodplains. The lower Devils River along the southwestern margin of the Edwards Plateau is a mesic outlier with a riparian forest of live oak, pecan and sycamore (Smith and Butterwick 1975a, Gehlbach 1981). Elevated, Quarternary gravel terraces occasionally support post oak (Quercus stellata) woodlands. Early descriptive accounts for the eastern portions can be found in Bray (1906) and Palmer (1920).

Riparian vegetation changes in response to an east-west moisture gradient, as well as available riparian water and soil depth. Most eastern deciduous species such as pecan, chinkapin oak, bur oak (Q. macrocarpa), elms (Ulmus spp.), ash (Fraxinus spp.), etc., extend no further west than on a line through Tom Green, San Saba, Menard, Kimble and Real counties.

Steep Slopes

The steep slopes of the Balcones canyonlands support short-stature woodlands which vary from evergreen juniper and juniper-oak on south and west exposures, to deciduous mixed-oak hardwood woodlands on north and east exposures (see Table 2a.-d.). Texas oak (Quercus texana) is usually the dominant in the east, but westward to the Nueces River on the southern margins of the Plateau, Lacey oak may dominate. Farther west to the Pecos, vasey oak (Q. vaseyana) is dominant. Some northern exposures are dominated by Texas ash (Fraxinus texensis) or locally big-tooth maple (Acer grandidentatum). In our treatment area, these forests often contain a distinct understory shrub layer, with yaupon (Ilex vomitoria), American beautyberry (Callicarpa americana), hoptree, Mexican buckeye (Ungnadia speciosa), red or yellow buckeye (Aesculus pavia), deciduous holly and rough-leaf dogwood are variously present. A few of these communities have been documented by Van Auken et al. (1979, 1980). These studies, as well as earlier works (Anderson 1904, Cuyler 1931) noted that substrate has an effect on the vegetation. Texas madrone (Arbutus xalapensis) and pinyon pine (Pinus remota) are Sierra Madrean elements which occur in this community but are restricted to favorable exposures and elevations west of the Colorado River.

Slope communities on dry southern and eastern exposures are primarily evergreen and dominated by Mexican juniper, often in nearly pure stands called cedar breaks. Live oaks, Mexican persimmon (Diospyros texana), shin or scalybark oak (Quercus sinuata var. sinuata), evergreen sumac (Rhus

BALCONES CANYONLANDS: SLOPE WOODLANDS 2a.

Generalized transect @ Ft. Hood, Bell Co., Tx.
Lampasas Cut-Plain

North and East exposures deep soils	South and West exposures shallow soils
Trees	**Trees**
Quercus muhlenbergii	Juniperus ashei
Acer grandidentatum	Quercus sinuata var. breviloba
Ulmus crassifolia	Q. fusiformis
Quercus sinuata	
Fraxinus texensis	
Juniperus ashei	
Juglans major	
Celtis laevigata	
Quercus texana	
Shrubs	**Shrubs**
Ilex decidua	Forestiera pubescens
I. vomitoria	Rhus virens
Viburnum rufidulum	R. lanceolata
Cornus drummondii	Sophora secundiflora
Rhamnus carolinia	Diospyros texana
Ptelea trifoliata	Berberis trifoliolata
Symphoricarpos orbiculatus	Zanthoxylem hirsutum
Forestiera pubescens	Yucca pallida
Berchemia scandens	
Ungnadia speciosa	
Sophora secundiflora	
Cercis canadensis	
Rhus aromatica	

BALCONES CANYONLANDS: SLOPE WOODLANDS 2b.

Generalized transect at Austin, Travis Co., Tx.

North and East exposures deep soils	South and West exposures shallow soils
Trees	**Trees**
Quercus texana	Juniperus ashei
Q. fusiformis	Quercus fusiformis
Juniperus ashei	Diospyros texana
Juglans major	
Fraxinus texensis	
Prunus serotina	
Ulmus crassifolia	
Q. sinuata	
Arbutus xalapensis	
Shrubs	**Shrubs**
Quercus sinuata var. breviloba	Berberis trifoliolata
Cercis canadensis	Sophora secundiflora
Ungnadia speciosa	Rhus virens
Eupatorium havanense	Eysenhardtia texana
Ilex vomitoria	Mimosa borealis
Forestiera pubescens	Rhus aromatica
Garrya lindheimeri	Bernardia myricaefolia
Aesculus pavia	Yucca treculeana
Ptelea trifoliata	Dasylirion texanum
Callicarpa americana	Nolina texana
Viburnum rufidulum	
Prunus mexicana	

Table 2 a.-d. Generalized transect of slope woodland communities on dissected uplands from east to west (mesic to xeric) across the Escarpment (=Balcones Canyonlands). Characteristic species for each community are ranked according to relative dominance of the most important woody perennials only.

BALCONES CANYONLANDS: SLOPE WOODLANDS 2c.

Generalized transect @ S. Central edge
of Escarpment
Bexar, Medina, Bandera, Kendall Counties

North and East exposures deep soils	South and West exposures shallow soils
Trees	**Trees**
Quercus texana	Juniperus ashei
Q. glaucoides	Quercus fusiformis
Juniperus ashei	Diospyros texana
Prunus serotina	Quercus sinuata var. breviloba
Juglans major	Sophora secundiflora
Arbutus xalapensis	Acacia spp.
Ulmus crassifolia	Rhus virens
Fraxinus texensis	Eysenhardtia texana
Celtis sp.	Mimosa borealis
Acer grandidentatum	Yucca spp.
	Dasylirion texanum
	Morus microphylla
Shrubs	
Garrya lindheimeri	
Ungnadia speciosa	
Aesculus pavia var. flavescens	
Diospyros texana	

BALCONES CANYONLANDS: SLOPE WOODLANDS 2d.

Generalized transect @ SW edge of Escarpment. Uvalde, Kinney
Edwards and Real Counties

North and East exposures deep soils	South and West exposures shallow soils
Trees	**Trees**
Quercus texana	Juniperus ashei
Q. glaucoides	Quercus fusiformis
Arbutus xalapensis	Q. pungens var vaseyana
Prunus serotina	Bumelia lanuginosa
Juniperus ashei	Morus microphylla
Juglans major	
Q. pungens var. vaseyana	
Q. sinuata var. breviloba	
Pinus remota	
Shrubs	**Shrubs**
Forestiera reticulata	Berberis trifoliolata
Garrya lindheimeri	Condalia hookeri
Lonicera albiflora	Acacia spp.
Ptelea trifoliata	Yucca spp.
Cercis canadensis	Eysenhardtia texana
Cercocarpus montanus	Salvia ballotaefolia
Rhus virens	Leucana retusa
Aesculus pavia var. flavescens	Sophora secundiflora
Diospyros texana	
Crataegus sp.	

Table 2. (Con't.)

virens), skunkbush sumac (R. aromatica), elbow bush (Forestiera pubescens), and Texas mountain laurel (Sophora secundiflora) may also be present. Scrub oak (Quercus pungens) is important in the west. These xeric woodlands usually contain no understory woody layer and are less diverse in woody species than deciduous woodlands on mesic north and west slopes previously discussed.

Slopes of the dissected portions of the Lampasas Cut Plain support communities like those of the Balcones canyonlands in the Escarpment zone between Bexar and Travis County, although Texas oak and Texas ash seem to be more important in the Cut Plain. Quantitative data of analogous communities may be found in Van Auken et al. (1979, 1980, 1981). Scalybark oak is very important on the Cut Plain. Neither madrone, Lacey oak nor pinyon occur on the Cut Plain and the endemic Yucca rupicola of the Plateau is replaced on the Cut Plain by the endemic Yucca pallida.

Composition of slope communities west of the Frio River changed dramatically. Woodlands are usually restricted to northern and eastern exposures and canyon bottoms, and taxa with a Mexican affinity become more important. Ashe juniper declines markedly in importance and at the Rio Grande in Val Verde County is almost absent. Shrubs such as blue sage (Salva ballotaefolia), sumac (Rhus spp.), leadtree (Leucaena retusa), cenizo (Leucophylum frutescens), Spanish dagger (Yucca treculeana), scrub oak, Vasey oak, sotol (Dasylirion spp.), agarito (Berberis trifoliolata), Acacia spp. and other xeric adapted species are among the dominants. The western manifestation of the escarpment vegetation is best described by Bray (1905), Tharp (1944), Webster (1950), Flyr (1966), Smith and Butterwick (1975a, 1975b) and by Johnston, et al. (unpubished).

Special features of the Escarpment zone include assorted karstic features such as sinkholes and grottoes which are well known but little studied (Smith and Butterwick 1975b; Williams 1977b). These features are especially significant because they harbor peripheral and insular biota representative of Mexican/Tropical or eastern temperate deciduous elements. Mesic microenvironments of these features and of steep, protected canyons in general harbor numerous plants whose main distribution lies in the forests of the Gulf Coastal Plain and include yaupon, eastern red cedar (Juniperus virginiana), Indian-cherry (Rhamnus carolineana), Scalybark oak, Carolina supplejack (Berchemia scandens), inland seaoats (Chasmanthium latifolium), spicebush (Lindera benzoin), and dwarf palmetto. Narrow endemics include sycamore-leaf snowbell (Styrax plantanifolia) and Philadelphus ernestii. Some typical "Mexican" species at the eastern distributional extreme include madrone, Mexican tea (Ephedra antisyphlitica), and the fern Anemia mexicana.

Communities of the Relatively Undissected Uplands and Broad Valleys

Uplands of the Edwards Plateau are not today and historically never were an expansive, open, treeless grassland. However, exclusive of the Llano Uplift region, a grassland-woodland mosaic currently exists on relatively deep upland soils across extensive portions of the Plateau. Historically, grasslands were probably more extensive than today, having been reduced by encroachment of woody species, due in part to introduction of domestic livestock and elimination of fire (see Smeins 1980). Likewise, tall and mid grass have been replaced by short grasses on much of the eastern two-thirds of the Plateau. The Lampasas Cut Plain also historically supported grasslands, although a more mature landscape with fewer flat or gently rolling areas suggest that grasslands probably formed a patchy mosaic with woodlands. The Llano Uplift contained some grassland, although more favorable soil moisture relations in some areas indicate that oak-hickory woodland along with mesquite or mesquite-oak woodland predominated.

Grassland Communities

Grasslands of the Balcones region are generally restricted to relatively flat divides and adjacent moderate slopes and broad, mature stream valleys. These areas have been heavily grazed by domestic livestock and subjected to various brush control techniques. Hence, they are patchy and dynamic in time. Variation in species composition caused by soils and aspect is difficult to separate from that due to past disturbance (Dunlap 1983, Fowler and Dunlap 1986). Allred (1956) considered the Plateau region a southern extension of the Mixed Prairie. Thus, well-watered, moderately grazed uplands of the region resemble tall grass communities, but increasing aridity to the west causes mid- and short-grass components to become increasingly important.

Little bluestem (Schizachyrium scoparium), Texas wintergrass (Stipa leucotricha), white tridens (Tridens muticus), Texas cupgrass (Eriochloa sericea), tall dropseed (Sporobolus asper), sideoats grama (Bouteloua curtipendula), seep muhly (Muhlenbergia reverchonii) and common curlymesquite (Hilaria belangeri) are among the dominants of moderately grazed areas (Smeins et al. 1976, Dunlap 1983). Heavily grazed grasslands and more xeric soils contain a larger proportion of short grasses such as curlymesquite, three-awn, Texas grama (Bouteloua rigidiseta), red grama (B. trifola), hairy grama (B. hirsuta), hairy tridens (Erioneuron pilosum) and Tridens muticus. Cedar sedge (Carex planostachys) is common in these grasslands.

Soil depth and texture is highly variable in most areas, and hence the grasslands may be extremely heterogeneous (Smeins et al. 1976). An example of the interaction of grazing and soils is found in Fowler and Dunlap (1986). Uplands of the Hays-Travis County area may support shortgrass communities, while slopes have more tall and mid grasses due to 1) a clayeyer, and hence more droughty soil on ridges, and 2) heavier grazing on ridges than adjacent slopes because of the behavior patterns of domestic livestock. Live oak, shin oak and woody species associated with these are components of the grasslands, forming clumps or mottes. These mottes, along with frequent short but steep scarps dominated by woody species give many areas a park-like physiognomy. On deep, mainly noncalcareous or moderately calcareous soil, Texas oak, post oak (Quercus stellata) and, especially on the east, blackjack oak (Q. marilandica) may be scattered or form woodlands alternating with grasslands in the uplands. Similar oak woodlands also occur along well-drained stream terraces.

Essentially all of the grasslands of the region are in some stage of secondary succession, and thus highly dynamic (see Beaty 1973). Although those grasslands may not have been devoid of Ashe juniper, invasion or thickening of this species has been observed to cause "cedar breaks" to form in former grasslands (Buechner 1944; also see Smeins 1980). Mesquite is also a woody component of these grasslands that has increased in density in many areas, and live oak, shin oak and other woody species such as persimmon, agarita, sumac, etc., may cover more area than in pre-European settlement times. Prickly pear (Opuntia spp.), noseburn (Tragia spp.), rabbit tobacco (Evax spp.) and zexmania (Zexmania hispida) are also common components.

Lampasas Cut Plain

Plant communities of the Lampasas Cut Plain are hardly distinct from those of the Balcones Canyonlands, but the general topography is flatter, there are fewer drainages and the character of the region as a whole is that of a grassland or open woodland (sensu Driscoll, et al. 1984; = savanna, Kuchler 1964), rather than a closed woodland or forest. Also, there are more northern elements and a larger extent of post oak-blackjack oak woodlands, especially in the east and where the Cut Plain contacts the western Cross-Timbers in the northwest. Southern elements such as Texas madrone, Lacey oak and Mexican pinyon are absent from woodlands while scalybark oak and bur oak are more important.

Although usually considered most closely related to Mixed Prairie (Allred 1956, Dodd 1968, Risser et al. 1981), grasslands to the north and east of the Lampasas Cut Plain are considered extensions of the True Prairie (Dyksterhuis 1946, Diamond and Smeins 1985). Thus, grasslands of the region in good condition contain tall, mid and short grasses such as little bluestem, Indiangrass, big bluestem (Andropogon gerardii), silver bluestem, Texas wintergrass, tall dropseed, sideoats grama and curlymesquite. Mesquite is also a woody component, and Ashe juniper forms "breaks," althougn not as extensively as in uplands of the Balcones Canyonlands. Common short grasses of more xeric soils or in heavily grazed areas are the same as those listed for the Balcones Canyonlands. Mesquite is commonly a problem for ranchers, especially in the west, and as in other regions of the Edwards Plateau, the landscape is patchy due to differential past grazing, brush clearing, and other land use practices in general.

Woodlands

In our treatment area, open mixed-oak woodlands occur on interfluvial divides, frequently over karstic features. Important species include post oak, live oak, cedar elm and Texas oak. Where sands occur, blackjack oak and Texas hickory (Carya texana) appear locally. These woodlands occur within a matrix of grasslands with affinities for the Blackland Prairie (True Prairie) to the east. Open live oak woodlands occur along broad stream valleys coastward from the steep canyonlands. Widely spaced trees occur in a mixed to tall grassland context. Many refer to this community type as Oak Savannah (Kuchler 1964). Overgrazing has caused a general trend of replacement of open grasslands by shrubby oak species and tall or mid grasses by short grasses (Buechner 1944).

The Llano Uplift, or Central Texas Mineral Region, has been the focus of more workers than has the limestone portion of the Plateau. Detailed modern vegetation and floristic studies of the region include Whitehouse (1931, 1933), McMillen et al. (1968), Butterwick (1979), Walters (1980) and Walters and Wyatt (1982). Deep, sandy soils support open oak-hickory woodlands. Cedar elm, Texas hickory, live oak, blackjack oak, and post oak are common. Texas oak and Ashe juniper, nearly ubiquitous on the central and eastern parts of the limestone plateau, are conspicuously absent. Where heavy textured soils occur, primarily over shales, a mesquite woodland predominates. Disturbance on all types of deep soil favors mesquite, persimmon and whitebrush (Aloysia gratissima). Specialized vegetation of granitic massifs (e.g., Enchanted Rock) is well documented by detailed studies (Whitehouse 1933, Walters and Wyatt 1982). These areas are particularly important as locales to investigate successional processes.

Fault Zone East of the
Escarpment and Blacklands

While most investigators recognize the Balcones Fault Zone south and east of the Plateau, few have described the distinctive vegetation which occurs there. A few investigators who describe this vegetation include Anderson 1904; Tharp 1926; Blair 1965; Collins et al. 1975;
Riskind 1980; Gehlbach 1984; Lynch 1962, 1971. This fault zone of downthrown eroded Cretaceous materials, mostly of chalks, claystones, and marls, forms gently rolling terrain with shallow clayey soils (Mollisols). Frequently, Quarternary lag gravels cap these hills, more prominently on the south than on the north. The zone is dissected by numerous streams (Fig. 2), which shelter a riparian gallery forest. Bald cypress occurs as a component between the Nueces and Colorado while bur oak and bastard oak occur from the Colorado to the Brazos. Otherwise, the gallery forest can also be characterized as an oak-elm-hackberry forest. Pecan, ash (Fraxinus pennsylvanica, texana; berlandieri (north to south)) and cottonwood are also important.

From the Medina River north and eastward the vegetation of this zone is a tension or transition zone of woodlands, savannah, and prairie. Grasslands grade into Fort Worth Prairie communities through the Lampasas Cut Plain northward and Blackland Prairie to the east. Both of these grasslands are most closely related to the True Prairie of the North American Mid-continent (Dyksterhuis 1946; Diamond 1983). Woodlands grade into the Cross Timbers to the north and the Post Oak Savannah to the east. From the Medina River southward, but extending as far north as the Colorado River, brushy species of the Tamaulipan thorn scrub become more important, especially on well drained substrates. Species such as Texas persimmon, guajillo (Acacia berlanderi), Spanish dagger (Yucca treculeana), sacahuista (Nolina texana), sotol (Dasylirion texana), little-leaf sumac (Rhus microphylla), spiny hackberry, snakewood (Colubrina texensis), mountain laurel, Mimosa spp., lime prickly ash (Zanthoxylem fagara) and blackbrush acacia become more common. Ashe juniper is common in this zone at least to the Nueces River on the south. On deeper soils mesquite, huisache and hackberry (Celtis reticulata) dominate with mid grass generally characteristic of Tamaulipan savannahs, such as Trichloris, Chloris, Bouteloua, Stipa, Sporoblous, Bothriochloa, Aristida, Hilaria and Erioneuron.

Northward from the Colorado, where chalk is exposed, vegetation is typical of the Balcones Escarpment (see Blair 1965, Beaty and Gehlbach 1975) and the dissected uplands of the Lampasas Cut Plain. In the zone between Waco and Dallas eastern red cedar may occur together with Ashe juniper, but it occurs as far south as the Blanco River.

To the east of the chalky, relatively steep Plateau margins is the Blackland Prairie. These grasslands once occurred over deep, clayey Vertisols. Few remnants of this once vast grassland remain. The climax dominants include little bluestem, big bluestem, Indiangrass, tall dropseed, and sideoats grama (Diamond and Smeins 1985). Flat divides on the Plateau proper also supported similar grassland. The few degraded grassy areas over native sod that remain in our region contain Texas grama, Texas wintergrass, buffalograss, curly-mesquite, three-awn, muhly, and a variety of short grasses and weedy forbs.

CONCLUSION

The environment of the Balcones Fault Zone/ Edwards Plateau region is highly variable, and supports forests, woodlands and grasslands. Superimposed on variation caused by these abiotic factors is variation caused by historical land use patterns. Variation in grazing history and various brush control techniques have created a particularly patchy landscape in the grasslands and woodlands. Thus, the influence of environmental variables is often obscured, and "fence line" contrasts can be viewed throughout.

We have referred to the Balcones Canyonlands as the most distinctive biotic region of Texas. It has abundant endemic biota: yet, despite its physiographic distinctness, the area stands out because it harbors an intermixture of biotic elements characteristic of adjacent regions. The mesic microsites and deep sandy soils of the Llano Uplift region contain eastern deciduous forest species, the southern margin harbors Tamaulipan thorn scrub elements, and the xeric portions contain elements from the Mexican Plateau and Chihuahuan Desert. Likewise, grasslands contain elements of the True Prairie, Great Plains (= Mixed) Prairie, Short Grass Prairie and Desert Plains Grassland. This mixing of floras, this aggregate biota which is unlike any other adjacent provincial unit (Blair 1950), is a result of the biogeographic history of the Edwards Plateau, along with its size and high degree of climatic, edaphic and topographic variation. Indeed, the Plateau functions as a wide ecotonal refuge, a filter, or melting pot wedged between the equally rich Austroriparian biota to the east and the Mexican biotas to the south and west. Its richness and distinctiveness cries out for investigation, discovery, and most importantly, for responsible, enlightened stewardship.

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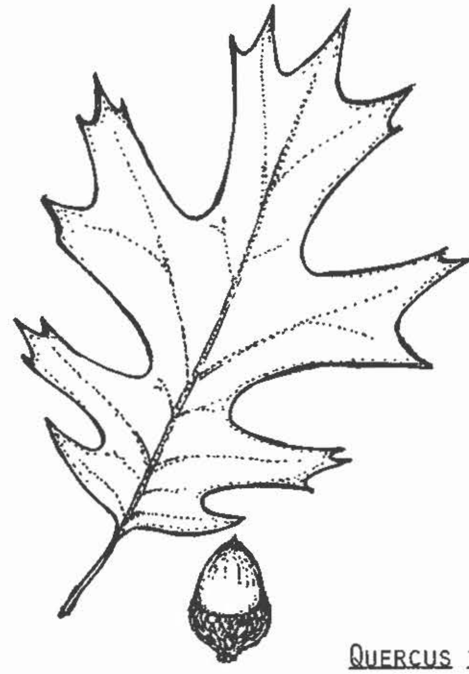
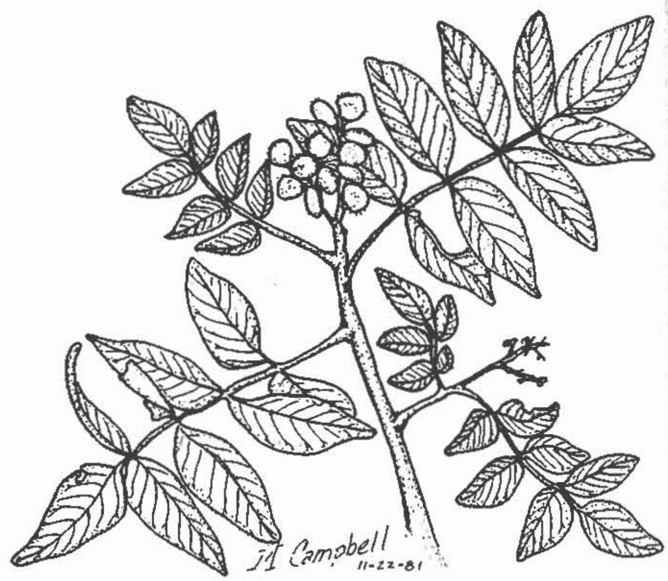


QUERCUS TEXANA
TEXAS OAK



RHUS VIRENS
EVERGREEN SUMAC

EDWARDS HEATH

Patrick L. Abbott
Department of Geological Sciences
San Diego State University
San Diego, CA 92182

The Edwards Plateau has been dissected by stream erosion to yield a rugged topography referred to locally as the "Hill Country." Its' main physiographic component is gently sloping interstream uplands. These relatively level uplands are interrupted by steep slopes and canyon walls of stream courses. The Edwards Plateau is a limestone terrane rife with fissures which carry water to springs which in turn keep the streams supplied.

The limestones of the upland divides are slowly carried off in solution by carbonic acid-laced water. The only particulate matter available to form a soil residuum is the minor percent of clay and sand admixed within the limestone. But the steepness of the slopes allows a rapid runoff of rain that commonly results in erosion of clastic material before a mature soil profile can develop. Thus the area is characterized by thin soils mixed with broken rock slabs that rest on hard limestone.

The region annually receives from 15 to 30 inches of rain but its distribution in time and space is highly irregular. Several years may see far less than the mean annual rainfall but then the precipitation during one week may exceed the yearly average. Mean annual temperature is in the high 60's but winter readings drop below freezing for short periods and summer values sometimes exceed 100°. Winds dominantly come from the southeast from the Gulf of Mexico and evaporation rates are considerably in excess of precipitation.

The eastern Edwards Plateau is covered by open grassland and scattered scrub timber. The timber of the divides is a dry-climate forest picturesquely described by Bray in a 1904 USDA Forestry Bulletin:

> "The growth is stunted, the wood dense and hard, the branches rigid, the foliage somber, the leaves small and stiff; the climate is written in every feature."

The native vegetation is largely short grasses, bunch grasses, abundant junipers, various oaks, mesquite, cacti, and many shrubs. It is used predominantly as range land and is commonly stocked with combinations of cattle, sheep and goats to make best economic use of the variety of plants.

The steep limestone slopes and gentler uplands are dominated by a juniper-oak-grass floral association. The most abundant tree is *Juniperus ashei*. This juniper (known as cedar to "Hill Country" folk) flourishes in the harsh calcareous soils of central Texas and on similar limestone terranes in southern Oklahoma and southeastern Missouri.

Oaks common to the area have geographic distributions over large parts of the Atlantic and Gulf coastal plains (Fowells, 1965). These oaks include *Quercus sinuata* (white or shin oak), *Q. virginiana* (live oak), and *Q. shumardii* (Texas or Spanish oak). The westernmost extent of each oak species on a range map is separated by a dashed line essentially delimiting the Balcones fault trace. West of this line these wide-ranging oak species have had to undergo ecotypic differentiation in order to adjust to the thin, seasonally dry, calcareous soils of the Edwards Plateau. Thus they are further described by the respective varieties: *breviloba*, *fusiformis*, and *texana*. The harsh soils derived from the limestone terrane and the spasmodic rainfall have caused habitat-correlated variation within each species that has created genetically fixed ecotypes. These varieties are found also in southwest Oklahoma and on the east face of the Sierra Madre Oriental in Mexico.

The distinctive stunted vegetation on the Edwards Plateau forms an extensive tract of wasteland known in other regions as a heath. This broad area of rather level, open, uncultivated land with poor soil and a dominant floral element creates an ambience that affects some people to the essence of their being. In psychological effect the Edwards Plateau and its vegetation create a mood not unlike that of the great heaths of southern England so memorably described by Thomas Hardy in the Return of the Native (1878). The following excerpt has been modified slightly from Hardy's original words.

> "The face of the heath by its mere complexion added half an hour to evening; it could in like manner retard the dawn, sadden noon, anticipate the frowning of storms scarcely generated, and intensify the opacity of a moonless midnight to a cause of shaking and dread.
>
> In fact, precisely at this transitional point of its nightly roll into darkness the great and particular glory of the Edwards waste began, and nobody could be said to understand the heath who had not been there at such a time. It could best be felt when it could not clearly be seen, its complete effect and explanation lying in this and the succeeding hours before the next dawn: then, and only then, did it tell its true tale. The sombre stretch of rounds and hollows seemed to rise and meet the evening gloom in pure sympathy, the heath exhaling darkness as rapidly as the heavens precipitated it. And so the obscurity in the air and the obscurity in the land closed together in a black fraternization towards which each advanced halfway.
>
> The place became full of a watchful intentness now; for when other things sank brooding to sleep the heath appeared slowly to awake and listen. Every night its Titanic form seemed to await something; but it had waited thus, unmoved, during so many

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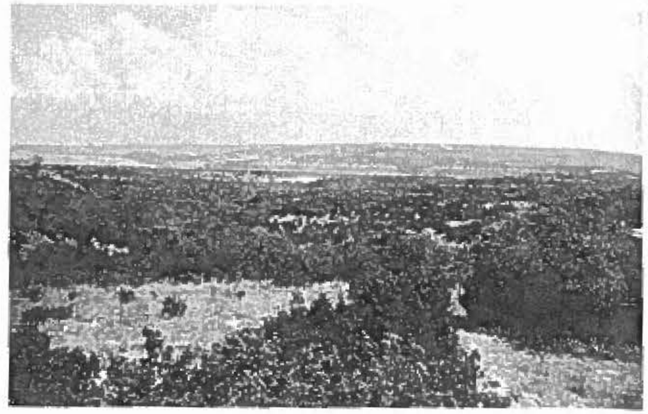
centuries, through the crises of so many things, that it could only be imagined to await one last crisis--the final overthrow.

It was a spot which returned upon the memory of those who loved it with an aspect of peculiar and kindly congruity. Smiling champaigns of flowers and fruit hardly do this, for they are permanently harmonious. Twilight combined with the scenery of Edwards Heath to evolve a thing majestic without severity, impressive without showiness, emphatic in its admonitions, grand in its simplicity. The qualifications which frequently invest the facade of a prison with far more dignity than is found in the facade of a palace double its size lent to this heath a sublimity in which spots renowned for beauty of the accepted kind are utterly wanting. Men have oftener suffered from the mockery of a place too smiling for their reason than from the oppression of surroundings oversadly tinged. Haggard Edwards appealed to a subtler and scarcer instinct, to a more recently learnt emotion, than that which responds to the sort of beauty called charming and fair.

The most thorough-going ascetic could feel that he had a natural right to wander on Edwards: he was keeping within the line of legitimate indulgence when he laid himself open to influences such as these. Colours and beauties so far subdued were, at least, the birthright of all. Intensity was more usually reached by way of the solemn than by way of the brilliant, and such a sort of intensity was often arrived at during winter darkness, tempests, and mists. Then Edwards was aroused to reciprocity; for the storm was its lover, and the wind its friend. Then it became the home of strange phantoms; and it was found to be the hitherto unrecognized original of those wild regions of obscurity which are vaguely felt to be compassing us about in midnight dreams of flight and disaster, and are never thought of after the dream till revived by scenes like this.



It was at present a place perfectly accordant with man's nature--neither ghastly, hateful, nor ugly: neither commonplace, unmeaning, nor tame; but, like man, slighted and enduring; and withal singularly colossal and mysterious in its swarthy monotony. As with some persons who have long lived apart, solitude seemed to look out of its countenance. It had a lonely face, suggesting tragical possibilities.

The untameable, Ishmaelitish thing that Edwards now was it always had been. Civilization was its enemy; and ever since its beginning its soil had worn the same antique brown dress, the natural and invariable garment of the particular formation. In its venerable one coat lay a certain vein of satire on human vanity in clothes. A person on a heath in raiment of modern cut and colours has more or less an anomalous look. We seem to want the oldest and simplest human clothing where the clothing of the earth is so primitive.

To recline on a stump between afternoon and night, where the eye could reach nothing of the world outside the summits and shoulders of heathland which filled the whole circumference of its glance, and to know that everything around and underneath had been from prehistoric times as unaltered as the stars overhead, gave ballast to the mind adrift on change, and harassed by irrepressible New. The great inviolate place had an ancient permanence which the sea cannot claim. Who can say of a particular sea that it is old? Distilled by the sun, kneaded by the moon, it is renewed in a year, in a day, or in an hour. The sea changed, the fields changed, the rivers, the villages and the people changed, yet Edwards remained. Those surfaces were neither so steep as to be destructible by weather, nor so flat as to be the victims of floods and deposits."

THE BALCONES FAULT ZONE AS A MAJOR ZOOGEOGRAPHIC FEATURE

Raymond W. Neck
Texas Parks and Wildlife Department
4200 Smith School Road
Austin, Texas 78744

ABSTRACT

The Balcones Fault Zone is a major influence on the geographic distribution of animals in central Texas. This influence is most evident in species which are directly influenced by edaphic factors or are closely associated with plants which are similarly influenced by edaphic factors.

INTRODUCTION

In an attempt to understand the non-random distribution of animal species on the face of the earth, zoogeographers have long attempted to delineate discrete geographical areas which possess significant internal homogeneity of faunal assemblages, especially in relation to adjacent areas with a different set of assemblages. Lines are drawn between such discrete areas after analysis of geographical ranges of individual species. Exact delineation of the boundary between adjacent regions is usually not possible, because zoogeographers realize (if only on a subconscious level) that these lines are an invention of the human mind. The resulting set of biotic regions is simply a model of the real biological world--not an exact picture of that world.

Meaningful analysis of the North American fauna from a zoogeographical viewpoint dates to the efforts of Dice (1943). He published a major contribution with cartographic delineations and verbal descriptions of many biotic provinces in North America from the Arctic frontiers to the Tropics Panama. Dice placed portions of biotic provinces within the boundaries of Texas.

The treatment by Dice of the biotic provinces of Texas was illuminating but fell short of being satisfactory. Such a lack of demonstration of faunal reality in the 1940's was not unexpected. Details of the distribution of animal species in Texas were unknown to most works outside the boundaries of the state, as Texas was far removed from the intellectual centers of the time.

The worker of the early twentieth century with the best knowledge of distribution of animal species in Texas was self-trained and had died in early 1933. Yet most areas of southern and western Texas were unknown to John K. Strecker of the Baylor University Museum. Hence, the total picture of the Texas fauna was unavailable to most biological workers in Texas at that time.

However, studies by one of the new breed of field biologists of the mid-twentieth century were sufficient to allow a refinement of Dice's biotic provinces with the resultant creation of a new biotic province - one which was totally enclosed by the capricious geographical boundaries of Texas.

W. Frank Blair came to The University of Texas in Austin in 1946. His early training was in mammals, but Blair later was to concentrate on amphibians and especially the true toads of the genus Bufo.

Blair's analysis of the biotic provinces of Texas was published in 1950. This paper marks the beginning of the study of zoogeography in Texas. No significant alterations of Blair's biotic provinces have been forthcoming. The original analysis (Blair 1950) remains the most often cited reference in the zoogeographic literature of Texas. The creation of the Balconian Biotic Province by Blair (1950) was brought about by the realization that the Balcones Fault Zone was a major physical factor in the distribution of animals in central Texas.

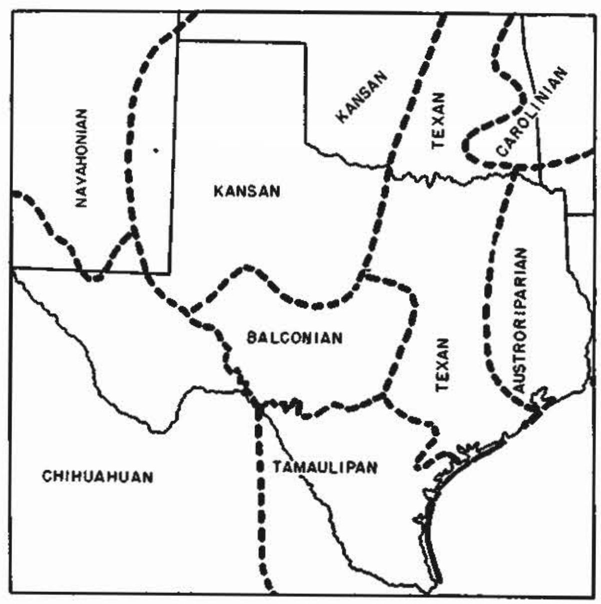


Figure 1. Biotic provinces of Texas according to W. Frank Blair (1950).

Personal field studies and perusal of pertinent literature by this author for over a decade have demonstrated variation in the relative distinctiveness of adjacent biotic provinces. Of all the biotic provinces now accepted by zoogeographers to occur in Texas (except for the Guadalupe Mountains which are included in the Navahonian Biotic Province), the Balconian Biotic Province is by far the most distinct. Clearly related to the surface exposure of an enormous (though highly faulted) block of Lower Cretaceous calcareous sedimentary rocks, the Balconian Province is most distinct along its east-

in Abbott, Patrick L. and Woodruff, C.M., Jr., eds., 1986, The Balcones Escarpment, Central Texas: Geological Society of America, p. 35-40

ern and southern edges. Boundary lines drawn on its western edge to delineate it from the Chihuahuan Biotic Province are related to increasing xericity. Similarly, the boundary along the northwestern and northern margins are rather vague but are related to changes in geological substrate.

The sharper delineation of the Balconian Biotic Province along its eastern (Texan Biotic Province) and southern (Tamaulipan Biotic Province) is a reflection of the sharper break in geological substrate. Biotic provinces are artifacts of human desires to order and classify the natural world; in reality, animals and their environments know no such tidy boundaries. This reality is the result of adjustments by animal species in response to variations in substrate, microclimatic, and vegetative environments along and to either side of the Balcones Escarpment.

The purpose of this paper is to analyze the distributions of animal species along the eastern edge of the Balconian Biotic Province. In this zone of complex geological changes, the environmental factors most important in controlling the distributions of animal species should be easily discernible. The zone in the area from Austin southwestward to New Braunfels and then west into the Texas Hill Country is the area discussed herein because of greater scientific knowledge in this area. Faunal range changeovers appear to be more dramatic in shorter distances here than elsewhere.

In recognition of his seminal work in the field of Texas zoogeography and his creation of the Balconian Biotic Province, I am pleased to dedicate this paper to the memory of W. Frank Blair (1912-1985). I can hope only that Frank would have enjoyed this analysis and, further, that this analysis may encourage future workers to devote additional intellectual investments to this area.

METHODS

Lists of vertebrate species and selected invertebrate groups which occur in central Texas have been generated. Species (or subspecies) have been designated as limited (east or west) or non-limited in reference to the effect of the Balcones Fault Zone on geographical range.

Analyses of the effect of the Balcones Escarpment upon species distributions for several faunal groups have been published (Buechner 1946; Smith and Buechner 1947). However, the narrative thrust of this paper is aimed more toward specific examples than a comprehensive numerical analysis of the faunal changes exhibited on either side of the Balcones Escarpment. A summary numerical analysis of the influence of the Balcones Escarpment is presented for various faunal groups, but more effort has been expended toward providing examples of paired species and subspecies. Detailed numerical analyses will be presented in a later paper.

NUMERICAL ANALYSIS

Analysis of the herpetofauna of central Texas by Smith and Buechner (1947) revealed that the majority of species (77%) of reptiles and amphibians are limited (either eastward or westward) by the Balcones Escarpment. The percentage of species thus limited varied among the major orders of the herpetofauna from 100% (salamanders) to a mere 67% (chelonians) Other orders had intermediate percentages of limited species as follows: snakes, 70%; anurans (frogs and toads), 74%; and lizards, 95%.

The dynamic nature of the boundaries of the geographical ranges of birds complicates any zoogeographical analysis of the effect of the Balcones Escarpment upon specific birds. Buechner (1946) reported that geographical ranges of 56% of the bird species occurring in central Texas were limited by the Balcones Escarpment.

Of the 128 species of nonmarine mammals listed by Davis (1974) from Texas, a total of 65 species (50.8%) occur along the Balcones Escarpment. Of these 65 forms, 34 species (52.3%) are limited by the escarpment while 31 species (47.7%) have an overlapping distribution. Of the 34 limited species, 18 (52.9%) are found only west of the Balcones Escarpment while 12 (35.3%) are found only east of this line.

GEOGRAPHICAL RANGE PAIR TYPES

Parapatric Species

Taxa whose geographical ranges meet with no significant overlap have parapatric ranges. Recognition of such pairs is dependent upon the ability to pair taxa as ecological analogues and/or phylogenetic relatives.

Several pairs of birds can be placed in this category. The eastern tufted titmouse (*Parus bicolor bicolor*) and the black-crested titmouse (*Parus bicolor atricristatus*) form an east-west pair of subspecies which have a very narrow zone of intergradation along the eastern margin of the Balcones Escarpment (Dixon 1978). Also forming an east-west pair are the red-bellied woodpecker (*Melanerpes carolinus*) and the golden-fronted woodpecker (*Melanerpes aurifrons*). The eastern taxa of these two pairs (and additional unlisted pairs) are typically found in broadleaf, deciduous woodlands while the western taxa is more typical of the more open, xeric woodlands of the Texas Hill Country (both broadleaf and coniferous woodlands).

An exceptionally interesting species pair is given by two salamanders which are members of two different families. The wide-mouthed salamander (*Ambystoma texanum*) of the family Ambystomidae ranges to the east of the Balcones Escarpment. While individuals of this species spend dry periods under logs in protected areas, eggs are deposited in water where larval development occurs. The slimy salamander (*Plethodon glutinosus*) of the family Plethodontidae is found in mesic canyons, caves, and limestone slopes in the Texas Hill Country. Dry periods are spent deep in talus slopes, rocky terraces, or caves; larval development is terrestrial but must occur in very mesic microhabitats. These two species of salamanders with differing phylogenetic and ecological histories meet along the eastern face of the Balcones Escarpment. Overlap is very narrow and occurs as isolated populations in a series of mesic canyon environments in the Texas Hill Country.

Another notable parapatric species pair involves the eastern ranging southern leopard frog (*Rana sphenocephala*) and the southern and western ranging Rio Grande leopard frog (*Rana berlandieri*). The boundary zone between these two forms is very narrow and is a definite example of true parapatry. However, this boundary zone is actually about 30 kilometers east of the Balcones Escarpment. The range boundary zone of these two species is apparently related to substrate and moisture relationships which are unrelated to the presence of a major physiographic break to the west.

Ground squirrels provide a mammalian example of a parapatric range pair. The Mexican ground squirrel (Spermophilus mexicanus) is found east of the escarpment in well-drained, generally non-rocky soils especially in open terrace habitats without significant woody vegetation. West of the escarpment the rock squirrel (Spermophilus variegatus) is found in talus slopes, canyons, and rocky uplands.

Eastern Sympatry - Western Allopatry

Other pairs of taxa exhibit overlapping geographical ranges (sympatry) east of the Balcones Escarpment, but only one species occurs to the westward of the escarpment (allopatry). In other words, one taxa of each pair ranges on both sides of the escarpment while the other pair occurs only east of the Balcones Escarpment.

Several examples of this distribution pair type are exhibited by reptilian species. The eastern box turtle (Terrapene carolina) ranges over most of the eastern United States; a western subspecies, the three-toed box turtle (Terrapene carolina triunguis), ranges westward to within 30 kilometers of the Balcones Escarpment. The three-toed box turtle is typically found in open woodlands dominated by hardwoods (post oak/black hickory). Occurring over much of eastern Texas westward through central Texas, the ornate box turtle (Terrapene ornata ornata) is found in prairies, savannahs, and open woodlands.

Another congeneric pair of species with a similar range is provided by the broad-banded copperhead (Agkistrodon contortrix laticinctus) and the western cottonmouth (Agkistrodon piscivorus leucostoma). The western cottonmouth is found in the southeastern United States as far west as the larger streams of the eastern Hill Country of Texas, although this snake is very rare in the Balcones Escarpment area. On the other hand, the broad-banded copperhead ranges from eastern Texas westward through central Texas. In this western portion of the range, the broad-banded copperhead is found in riparian areas as it approaches the aquatic habitat of the cottonmouth.

A pair of congeneric aquatic species is provided by the yellow mud turtle (Kinosternon flavescens flavescens) and the Mississippi mud turtle (Kinosternon subrubrum hippocrepis). The yellow mud turtle ranges from southern Nebraska to northern Mexico; in central Texas, it exists both east and west of the Balcones Escarpment. The Mississippi mud turtle ranges from the bottomlands of the Mississippi River westward to the creeks with more dependable flow, such as those occurring along the Balcones Escarpment.

The large, vociferous jays provide another species pair example. The blue jay (Cyanocitta cristata) occupies mesic, broad-leaved woodlands from the Atlantic coast westward through central Texas to the well-watered canyons in the Texas Hill Country. The scrub jay (Aphelocoma coerulescens) occupies xeric, evergreen woodlands from the Pacific coast to the western margins of the Balcones Escarpment Zone.

The narrow-mouthed toads are small anurans which feed on ants and other small insects. The eastern narrow-mouthed toad (Gastrophryne carolinensis) ranges from the southeastern United States westward to about 30 kilometers east of the Balcones Escarpment. A related species, the Great Plains narrow-mouthed toad (Gastrophryne olivacea), ranges from western Mexico through central Texas almost to the Texas-Louisiana boundary. While both species are found in terrestrial microhabitats during the dry season, the eastern narrow-mouthed toad is found in areas of more constant water supply while the Great Plains narrow-mouthed toad is found in areas without persistent water supplies.

Western Sympatry - Eastern Allopatry

As an analogue to species discussed in the previous section, another type of species-range pairs includes species which are sympatric west of the Balcones Escarpment; only one species of each pair exists east of the escarpment.

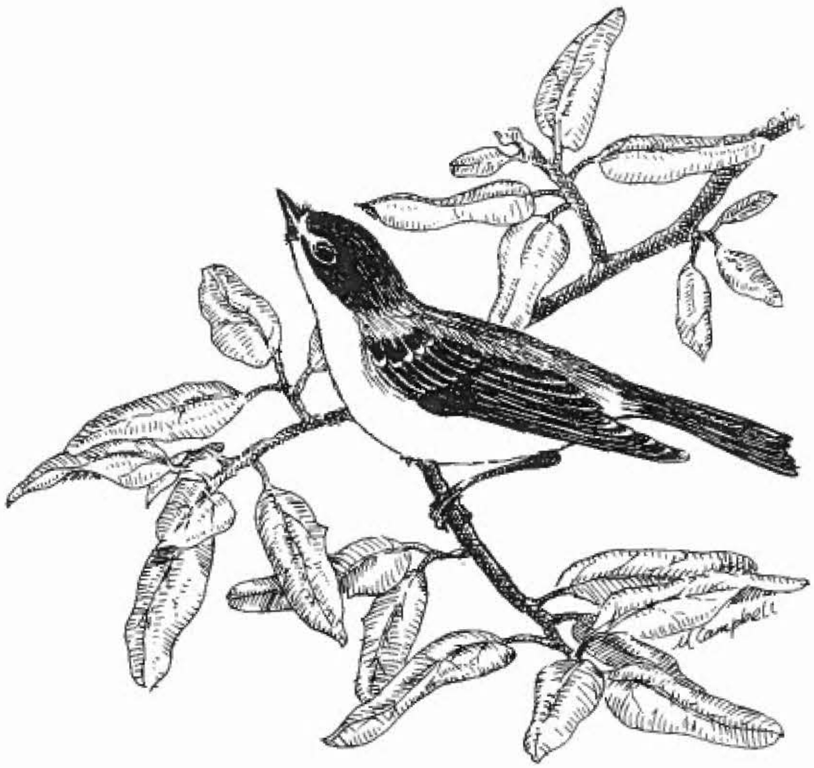
The phylogenetically-varied group of mammals which are classified as "squirrels" provide a species pair of this type. The wide-ranging fox squirrel (Sciurus niger) is certainly most common east of the Balcones Escarpment where it is found in bottomland and upland woods, i.e. woodlands consisting entirely or largely of broad-leaved trees. However, a significant portion of the natural range of this species exists in riparian and canyon woodlands of the Texas Hill Country. The pairing of the fox squirrel, a "true squirrel," with the previously-mentioned rock squirrel, a "ground squirrel," may seem anomalous. However, these two species have substantial overlap in their diet, and, thus, form a pair of ecological analogues. Ecological interactions occur in ecotonal areas of mesic canyon systems in the Texas Hill Country where the fox squirrel and rock squirrel are found in mesic and xeric areas, respectively.

Two scorpions also occur sympatrically west of the Balcones Escarpment, whereas only one occurs east of that area. The striped scorpion, Centruoides vittatus, ranges over most of Texas where it is found in mesic and xeric woodlands, savannahs, and prairies. A rock scorpion, Vejovis reddelli, is found over much of the Texas Hill Country but is unknown east of the Balcones Escarpment.

Similarly, two congeneric woodland snails have partially sympatric ranges. Polygyra texasiana ranges from eastern Texas through central Texas to the western Hill Country, where it is found in woodlands, savannahs, and those prairies with sufficient downed wood to provide cover for reduction of water loss. The similar-appearing, but smaller Polygyra mooreana, is found in the Texas Hill Country, where it occurs in xeric broadleaf and coniferous woodlands.

Endemic Species

A number of aquatic species are endemic to thermally and physicochemically stable waters in spring-run streams of the Balcones Escarpment and the Texas Hill Country. Freshwater mussels (family Unionidae) endemic to the Hill Country include



BLACK-CAPPED VIREO

GOLDEN-CHEEKED WARBLER

Quincuncina mitchelli, Lampsilis bracteata, Quadrula petrina, and Quadrula aurea. The freshwater gastropod, Elimia comalensis, is restricted to spring-run streams of the Balconian Biotic Province.

Two bird species are endemic to the central Texas area, at least as far as breeding range is concerned. Both the black-capped vireo (Vireo atricapilla) and golden-cheeked warbler (Dendroica chrysoparia) breed nowhere but in xeric woodlands of central Texas. Substantial portions of the breeding range occur north of the true Hill Country in the Lampasas Cut Plains. The Lampasas Cut Plains also are located west of the Balcones Escarpment, although the vertical displacement is not visible at the surface. Interestingly, these two endemic breeders are found in very distinct but often adjacent (even anastomosing) habitats. The black-capped vireo nests in thickets of scrub deciduous oaks, while the golden-cheeked warbler nests in woodlands of mature Ashe juniper trees with long bark strands.

Endemic amphibians include a variety of species which are found in rocky epigean habitats and hypogean (cave) habitats. Species include the cliff frog (Syrrophus marnocki), Texas blind salamander (Typhlomolge rathbuni), San Marcos salamander (Eurycea nana), and several blind salamanders (Eurycea latitans, E. troglodytes, E. tridentifera).

A large number of species of aquatic snails are found in aquifer habitats of both the Edwards and Trinity-Edwards aquifers (Hershler 1986). Other invertebrate and vertebrate species are also restricted to such subterranean habitats (Longley 1981). At least one terrestrial gastropod is endemic to the Balcones Fault Zone; Mesodon leatherwoodi is restricted to very mesic box canyons.

Range-Limited Single Species

A number of species which are limited geographically by the Balcones Fault Zone have no obvious ecological analogue on the opposite side of this zone. Eastern species in this classification include American alligator (Alligator mississippiensis), southern flying squirrel (Glaucomys volans), and red-headed woodpecker (Melanerpes erythrocephalus). Western species in this grouping include cliff frog, barking frog (Hylactophryne augusti latrans), red-spotted toad (Bufo punctatus), green toad (Bufo debilis), and black-tailed rattlesnake (Crotalus molossus).

A small group of western species are known to have outlier populations east of the Balcones Escarpment. Both the Texas alligator lizard (Gerrhonotus liocephalus infernalis) and the woodland snail Polygyra mooreana are known to have populations in an area of caleareous sandstone downstream on the Colorado River (Oakville Cuesta at La Grange, Fayette Co.). Polygyra mooreana also lives on Goliad Sandstone at Goliad State Park, Goliad Co. (downstream on San Antonio River).

FAUNAL HISTORY

Prior to the initiation of major faulting activity in what is presently central Texas, no sharp environmental boundary is believed to have existed. Certainly, environmental conditions were quite different from modern conditions due to the closer proximity of the coast as well as differences in global climate and continental configuration. The historical origin of the Balconian Biotic Province occurred when the environment on either side of the newly-created (and probably yet developing) escarpment became differentiated sufficiently to restrict animal species to only one side of the escarpment. This general statement merely states the obvious and demonstrates ignorance of the temporal genesis and development of the Balconian Biotic Province. While faulting began during the Miocene, the length of the activity period is unknown as is the degree and constancy of the rate vertical displacement. Whether significant effects on geographical ranges of animal species commenced in Late Miocene, Pliocene, or Pleistocene times is unknown. Portions of the aquifer fauna may date to Late Cretaceous time when an extensive cave system developed in Lower Cretaceous sediments.

Fossil Quaternary faunas known from sediments in the Texas Hill Country and Edwards Plateau have revealed that significant biological changes have occurred since the beginning of the Holocene. Unfortunately, correlative faunas from east of the Balcones Escarpment are not available (and may not exist). As recently as 8000 B.P., the eastern chipmunk (Tamias striatus) was living in the western Hill Country (Schultze Cave, Edwards County - Dalquest et al. 1969). This species is not known to live anywhere in Texas today. Historical records of the pine vole (Pitymys pinetorum) are known from Kerr County separated from its main range by at least 450 kilometers. Persistence of this species to the present indicates that a portion of the mesic-adapted fauna survived in the Balconian Biotic Province to the present.

HUMAN IMPACT

Alteration of the natural environments along the Balcones Escarpment by human activities in the last 150 years have also affected the distribution of numerous animals in this area. Eastern species, such as the bluejay, fox squirrel and the snail Polygyra texasiana, are more common now or are now present west of the Balcones Escarpment after major human utilization of central Texas. Alteration of intact natural communities in the Texas Hill Country has caused a general xerification of the environment. This xerification has allowed certain western species, e.g., the house finch (Carpodacus mexicanus), to extend eastward. In this instance, the western-ranging house finch now exhibits a narrow sympatry with the eastern-ranging purple finch (Carpodacus purpureus).

SUMMARY

A large percentage of the animal species occurring in central Texas are limited to either the eastern or western side of the Balcones Escarpment. Going from east to west, general environmental conditions change in several ways. Ambient conditions become less humid and somewhat cooler. Precipitation decreases in total amount but short-term rainfall totals increase. Substrate changes abruptly at the Balcones Escarpment, although some substrate changes occur east of the escarpment. Species most likely to have geographical ranges limited by the escarpment are those whose life cycle is totally or partially associated directly with the substrate, e.g., soil burrows, or hydrologic effects of faulting (the spring fauna). Other species may be associated with plant communities whose distribution is limited directly by the escarpment.

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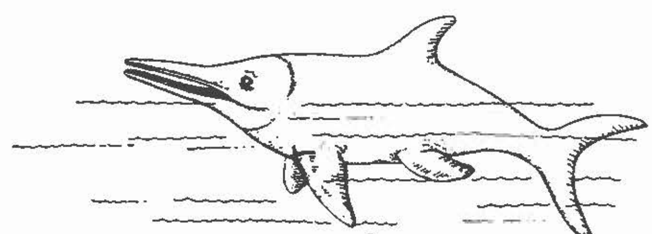

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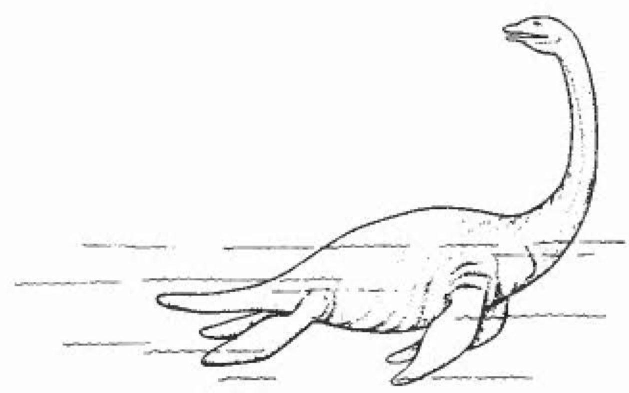

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VERTEBRATE PALEONTOLOGY OF THE BALCONES FAULT TREND

Ernest L. Lundelius, Jr.
Department of Geological Sciences
University of Texas at Austin
Austin, Texas 78713

ABSTRACT

Vertebrate fossils are known from numerous localities of Cretaceous and Quaternary age in the Balcones fault zone. Cretaceous vertebrate remains range in age from Neocomian to Maastrichtian and represent the following groups, Chondrichthyes, Osteichthyes, and Reptilia (Ichthyosauria, Plesiosauria, Squamata, Crocodilia, Pterosauria, Saurischia and Ornithischia). Trackways of both ornithischian and saurischian dinosaurs are known from the Glen Rose Formation.

Quaternary vertebrates are known from cave deposits of the Edwards Plateau and terrace deposits on the Gulf Coastal Plain. The mammalian assemblages from these deposits provide data on the Pleistocene and Holocene environments of Central Texas.

INTRODUCTION

The Balcones fault trend, as a fault system, extends southward from Waco, Texas through Austin and San Antonio. It then turns westward towards Del Rio and crosses the Rio Grande River into Mexico. This fault system, and its associated fault-line scarp, is the dividing line between the Edwards Plateau and the Gulf Coastal Plain. Over most of this distance the faulting juxtaposes Lower Cretaceous marine limestones, forming the Edwards Plateau, against Upper Cretaceous marine chalks and shales that underlie the western margin of the Gulf Coastal Plain. The area considered here is approximately two counties (50 miles) wide on each side of the fault zone; data from other parts of the Edwards Plateau and the Gulf Coastal Plain have also been used. The vertebrate fossils found in these sedimentary rocks have added significantly to knowledge of the faunal history of this region. Most of these fossils have been recovered from the Cretaceous limestones, shales and chalks and from the Pleistocene cave deposits of the Edwards Plateau and alluvial deposits of the streams that traverse the area. A few marine vertebrates are known from the Kincaid Formation of Paleocene age.

CRETACEOUS

Vertebrate fossils of Cretaceous age are sparsely distributed throughout the Balcones fault trend. Those on the Edwards Plateau are from Comanchean rocks ranging in age from Neocomian to lower Cenomanian. Cretaceous vertebrates from the Gulf Coastal Plain are from Gulfian rocks ranging in age from upper Cenomanian to Maastrichtian. In general the specimens are much more fragmentary and less common in central Texas than in north and northeast Texas. This is probably the result of much shallower water and lower depositional rates on the San Marcos platform of central Texas (Young, 1986).

Class Chondrichthyes

The teeth of sharks occur in most of the Cretaceous formations but are most abundant in the Upper Cretaceous strata from the Eagle Ford through the Navarro. Taxonomic identification of sharks based on teeth is uncertain, but all those from Cretaceous rocks of this area appear to belong to living groups and they have been assigned to modern genera. Teeth of a ray-like shark of the genus Ptychodus are common in the Eagle Ford. Rostral teeth of sawfishes of the genus Ischyrhiza are known from the Taylor Formation (Campanian) of Travis County (McNulty and Slaughter, 1964).

Class Osteichthyes

Remains of bony fishes are uncommon in Cretaceous rocks of this area. Tooth plates with rows of button-like teeth from pycnodont fish are found in lagoonal facies of the Lower Cretaceous Walnut and Glen Rose formations. These deep-bodied fish probably inhabited the quiet water lagoons behind the reefs. Their crushing teeth suggest that they fed on hard-bodied animals, perhaps corals or rudistids. At least one genus (Proscincetes = Microdon) is represented.

Order Chelonia

No turtle material of any consequence has been reported from the region considered here. Fossil turtles of a number of groups representing both fresh water and marine forms have been found farther north from both middle and Upper Cretaceous rocks (Langston, 1974; Thurmond, 1969; Zangerl, 1953).

Order Ichthyosauria

Two vertebrae of marine fish-like ichthyosaurs have been found in Travis County, one from the Del Rio Formation. No locality or stratigraphic data are known for the other. Isolated vertebral centra have been reported from the Ft. Worth Limestone and the Duck Creek Limestone farther north (McNulty and Slaughter, 1962; Slaughter and Hoover, 1963). With one possible exeption all Cretaceous ichthyosaurs can be assigned to a single genus, Platypterygius, with two species occurring in North America (McGowan, 1972). Presumably the material from Texas is assignable to this genus but isolated vertebrae are inadequate for positive identification.

Order Plesiosauria

Another group of large marine reptiles, the Plesiosauria, occur in the middle and Upper Cretaceous rocks of the Balcones fault trend. These plesiosaurs have been reviewed by Storrs (1981). Two genera of short-necked plesiosaurs are known from the area considered here, Trinacromerum from the Austin Chalk of Williamson

in Abbott, Patrick L. and Woodruff, C.M., Jr., eds., 1986. The Balcones Escarpment, Central Texas: Geological Society of America, p. 41-50

County and the Wolfe City Member of the Taylor Formation of McClennan County, and Brachauchenius from the Eagle Ford of Travis County.

Long-necked plesiosaur remains are known from the Eagle Ford Formation of Bell and McClennan counties, but are not sufficient to allow generic identification. Better material from farther north indicates that at least four genera, Elasmosaurus, ?Thalassomedon, Alzadosaurus and an indeterminate cimoliasaurid, are represented in Cretaceous rocks of the Texas Gulf Coastal Plain and it is likely that the indeterminate specimens from the Balcones fault trend belong to one or more of these taxa.

Order Squamata

A poorly known reptile, Coniasaurus, has recently been found in the Eagle Ford Group of Texas (Bell et al., 1982). Remains of these reptiles, previously known only from England, have been recovered from Travis, Bell and McClennan counties in the Balcones fault zone and from farther north in Dallas County where they occur in the Lower Britten Formation of late Cenomanian age. This was a small (1-2 ft. in length) lizard related to the living monitors of the Old World.

Another group of marine reptiles, the mosasaurs, is also found in Gulfian rocks of central Texas. Isolated vertebrae and other bones are not uncommon in the Austin, Taylor and Navarro groups. According to Thurmond (1969) nine taxa of mosasaurs occur in Texas Gulfian rocks, although not all of them are known from the Balcones fault trend. The oldest mosasaur remains from Texas come from low in the Eagle Ford in Dallas County (Thurmond, 1969). Another early specimen is from the Eagle Ford-Austin contact in McLennan County identified by Lucas as Clidastes (Hill, 1901). The very large genus Mosasaurus, first found in Europe in 1779, occurs in Taylor rocks in the city of Austin.

Order Crocodilia

Crocodilians are represented by a portion of a pelvis from the Travis Peak Formation and by dermal scutes of a large crocodilian (Dakotasuchus) from the Cow Creek Sandstone of western Travis County (Langston, 1974). Two partial skeletons of small (approximately 2 feet) crocodilians are known from the lower Glen Rose of Kendall and Medina counties (Langston, 1974). The Medina County specimen comes from an algal bed about twenty feet below the Corbula bed. This horizon, which also contains pholad borings, mudcracks, dinosaur tracks, casts of dinosaur vertebrae and scratch marks which may have been made by a pterosaur, has been interpreted by Stricklin and Amsbury (1974) as a surface subjected to brief subaerial exposure. The locality and horizon of the Kendall County specimen is unknown. Other fragmentary crocodilian remains have been recovered from the Navarro Formation of eastern Travis County.

Order Pterosauria

Pterosaurs are known from several fragmentary specimens from central Texas. The light, extremely thin-walled bones of these animals facilitate their assignment to this group. Langston (1974) reports a well preserved first phalanx of a wing finger from the Buda Formation in Hays County. There is also in the collection of the Texas Memorial Museum of the University of Texas a fragment of a long bone of a pterosaur from the Eagle Ford Formation of Travis County. Some tracks from the Glen Rose Formation in Medina County were possibly made by a pterosaur (Langston, 1974).

Order Saurischia

Skeletal remains of saurischian dinosaurs from the Balcones fault trend are rare although a number of forms are known from farther north (Langston, 1974). Only one occurrence of any importance is known; fragments of a skull and cervical vertebrae, a radius and a metacarpal referred by Langston (1974) to th e sauropod, Pleurocoelus. The material was found on the lee side of a rudistid reef in the middle part of the Glen Rose Formation in Blanco County.

Vertebrate Ichnology

The most common vertebrate fossils in the Cretaceous of the Balcones fault trend are footprints and trackways, mostly of dinosaurs and mostly from the Glen Rose Formation. They are widely distributed in central Texas (Fig. 1) and occur at a number of levels within the Glen Rose, and younger formations (Pittman, Pers. Com; Perkins and Stewart, 1971). The tracks in the Paluxy River near the town of Glen Rose are close to the contact of the Glen Rose Limestone and the under-

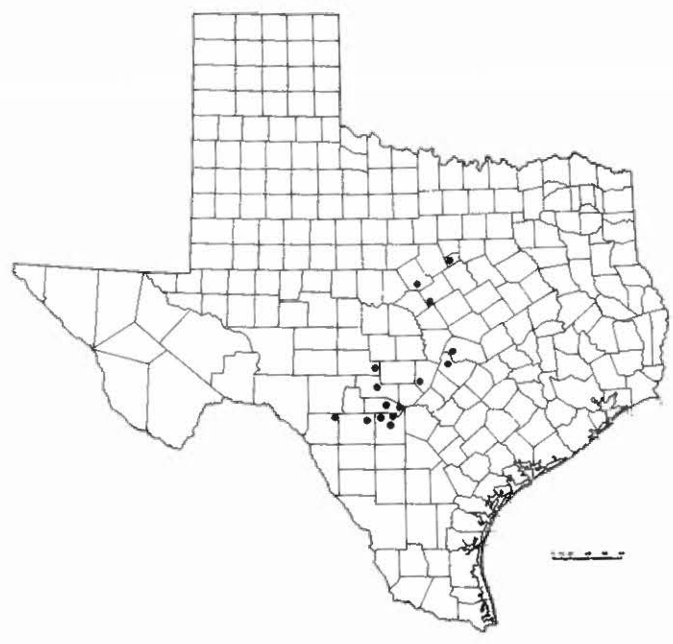

Figure 1. Map showing locations of dinosaur tracks in the Glen Rose Formation of central Texas (Modified from Langston, 1974). Scale in miles.

lying Bluff Dale Sandstone (Rodgers, 1967). Tracks on the south San Gabriel River in Williamson County are on the upper surface of the Glen Rose Limestone (Perkins and Stewart, 1971). Some trackways in Medina County are located below the Corbula bed in the lower Glen Rose Formation (Stricklin and Amsbury, 1974). The first report of dinosaur tracks in Texas was that of Shuler (1917) on tracks near Glen Rose, north of the Balcones fault zone. Little technical work was done on these tracks for many years and most of the reports were descriptive. Bird (1939, 1941, 1944, 1954, 1985) reported and described a number of occurrences in a series of popular articles.

Three distinct types of tracks are represented in the Comanchean rocks of central Texas. One consists of tridactyl tracks with long slender toe marks, a narrow "heel" and may or may not have claw marks. These have been assigned to the ichnogenus Eubrontes but Langston (1974) placed them in Irenesauripus and suggests that they were made by a large carnosaur.

A second type of tridactyl track, usually smaller than Irenesauripus, has short, blunt digits that diverge widely and a broader, rounder "heel". These were assigned by Langston (1974) to Gypsichites and probably represent an ornithischian dinosaur. The exact affinities of the dinosaur that made these tracks is uncertain. Although the tracks resemble those of iguanodontids, Langston (1974) pointed out that the only definitely known iguanodontid from the Comanchean is Tenontosaurus which had four toes while the Glen Rose tracks only show three.

A third category of tracks show a lack of claws on the front feet and the presence of four claws on the hind feet; they were made by a large sauropod. Langston (1974) suggested that the animal that made the tracks was Pleurocoelus which is known from skeletal remains from related deposits.

Some trackways have been the basis for speculation about the behaviour of dinosaurs. Bird (1944) described a large number of tracks from the Davenport Ranch in Bandera County. There were 23 individual trackways of sauropod dinosaurs with a maximum divergence angle of about 25° (Ostrom, 1972). In addition there were four sets of three-toed tracks which Ostrom (ibid) believed to have been made by theropods. Two of the theropod trackways paralleled the sauropod trackways and two were oriented at right angles to the sauropod trackways. Bird (1944) suggested that the common orientation of the sauropod trackways indicated that sauropods were gregarious animals. Ostrom (1972) has more recently given a more critical discussion of the subject of the implications of the trackways for dinosaur behaviour and arrived at essentially the same conclusion as Bird. Later work by Farlow (1981) on three theropod trackways from Kimble County has concluded that the animals that made these tracks were moving at 30, 40 and 43 kilometers per hour.

An analysis of the tracks provides information on the locomotion of some dinosaurs and on water depth in the area the tracks. Bird (1944) reported a sequence of sauropod tracks from Bandera County consisting only of fore-foot prints in a straight line. Where the trackway turns to the right there is a partial track of a left hind foot with the claws spread which was used to change the animal's direction. Bird's interpretation that the animal was afloat and used the hind foot only to change direction is probably correct.

The tracks of a carnosaur on the top of a monopleurid biostrome in Bandera County have been used by Perkins (1974) to infer the depth of water for monopleurids. The size of the tracks (one foot) indicates an animal no more than ten feet high in walking position. The tracks show no sign of sliding from which Perkins infers that the water was too shallow to offer any support for the body, probably not more than three or four feet deep. The surface with the tracks is overlain by more monopleurid reefs. Assuming the tracks were made at low tide and excluding large sea-level changes, Perkins concluded that water depth over the monopleurid beds was unlikely to be more than 10-12 feet. There is no conclusive evidence of subaerial exposure of these reefs at that time which suggests that, like the sauropods, theropods also ventured out into shallow marine water.

The Cretaceous-Tertiary contact is present in the eastern part of the area considered here. Although it has been investigated in connection with the Cretaceous extinction event (Hansen, 1982; Jiang, 1980) the record of fossil vertebrates is too sparse to be useful.

Quaternary

Quaternary faunas are known from caves in the Cretaceous limestones of the Edwards Plateau and from fluvial deposits on terraces of the streams that cross the Balcones fault zone. All of the known faunas, with one exception, are Rancholabrean or Holocene in age.

The locations of the faunas discussed here are shown in Fig. 2. The data on late Pleistocene and Holocene faunas for Central Texas was summarized by Lundelius (1967). This paper draws on that report, which dealt essentially with the mammalian species, with additions and corrections resulting from new information.

The Balcones fault zone is today an ecologically diverse area. The Balcones fault has placed the hard resistant limestones of the Edwards Plateau against the less resistant shales and chalk of the Gulf Coastal Plain. This has resulted in the formation of the Balcones escarpment and the dissection of the eastern and southern edges of the Edwards Plateau to form deep and humid canyons separated by relatively dry divides. The outer edge of the Gulf Coastal Plain is a low relief rolling surface with broad stream valleys. It is this diversity in topography and substrate that is the basis for the environmental diversity. The change in substrate, topography and elevation that takes place at the Balcones escarpment makes this an important biological boundary as well as a physiographic boundary as was recognized by Blair (1950). An examination of the distributions of Pleistocene faunas shows that this was also the case at that time.

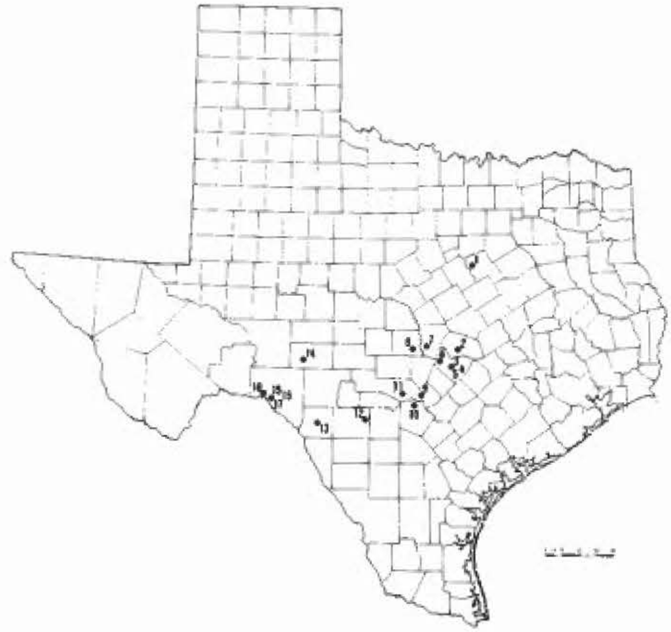

Figure 2. Map showing the locations of Quaternary localities mentioned in the text. 1 Kyle site, Hill County; 2 Laubach Cave, Williamson County; 3 Fyllan Cave, Travis County; 4 Mac's Cave, Travis County; 5 Barton Road site, Travis County; 6 Levi Shelter, Travis County; 7 Longhorn Cavern, Burnet County; 8 Miller's Cave, Llano County; 9 Wunderlich site, Comal County; 10 Friesenhahn Cave, Bexar County; 11 Cave Without a Name, Kendall County; 12 Kincaid Shelter, Uvalde County; 13 Rattlesnake Cave, Kinney County; 14 Felton Cave, Sutton County; 15 Centipede Cave, Val Verde County; 16 Damp Cave, Val Verde County; 17 Cueva Quebrada, Val Verde County; 18 Bonfire Cave, Val Verde County. Scale in miles.

Most of the fossil localities are caves that have been opened to the surface by the dissection of the edge of the Edwards Plateau. The few fossil localities that are known from the Gulf Coastal Plain are from terrace deposits. Approximately half of the localities are archaeological sites. The assemblage of animals from each type of site is biased in different ways. With some exceptions (e.g. Friesenhahn Cave, Kincaid Shelter, Bonfire Shelter and Cueva Quebrada) larger animals are poorly represented in cave deposits when compared to open terrace sites, which frequently do not have a good representation of small animals. Archaeological sites usually have assemblages strongly biased in favor of those species used as food by aboriginals.

Middle Pleistocene Faunas

The oldest known Pleistocene fauna is from Fyllan and Kitchen Door caves immediately west of the Balcones fault zone in Austin, Travis County. These completely filled caves are exposed in a limestone quarry. The faunas have been studied by Taylor (1982) who considered them to be of mid-Irvingtonian age, partly on the basis of resemblance to Irvingtonian faunas in other parts of North America. The muskrat represented is assignable either to *Ondatra hiatidens* or *O. annectens*. *O. annectans* is known from such Irvingtonian faunas as Cudahy, Kansas; Conard Fissure, Arkansas; Trout Cave, West Virginia and Cumberland Cave, Maryland. *O. hiatidens* is known from Port Kennedy Cave, Pennsylvania. Paleomagnetic analysis of the sediments surrounding the fossils indicates that they originally had reversed polarity. This indicates a minimum age of .73 m.y. B.P. which agrees with the faunal evidence.

The Fyllan Cave fauna contains remains of animals indicative of a wide variety of habitats. Some, such as the microtine rodents (*Atopomys texensis*, *Pitymys guildayi* and *Ondatra* c.f. *annectens* or *O. hiatidens*) and a tapir, (*Tapirus* sp.) indicate the presence of habitats more mesic than the present. More open habitats are indicated by horse (*Equus*), antilocaprid and the large extinct peccary, *Platygonus*. In general, the fauna indicates a climate with a more equable climate than today and the presence of diverse habitats.

Late Pleistocene Faunas and Environments

All of the other known Pleistocene faunas from the Balcones fault zone are Wisconsinan in age. All of the available radiocarbon dates are younger than 30,000 years B.P. Most of the material is from cave deposits but some material has been recovered from terrace deposits. The material from the terrace deposits is not abundant and has not been studied carefully. As a result the degree, nature and significance of the faunas from the various terraces of the streams are not understood. The following discussion is based almost entirely on cave faunas.

Faunas of late Pleistocene age from this region are made up of three categories of species. One is made up of extinct species such as *Mammuthus jeffersonii* (Jeffersonian mammoth), *Mammut americanum* (American mastodon), *Smilodon floridanus* (sabertoothed cat), *Canis dirus* (dire wolf), *Glossotherium harlani* (Harlan's ground sloth) and other species, mostly of large size, that are usually considered to be characteristic of the Pleistocene. Most of these species disappeared between 10,000 and 11,000 years BP (Martin, 1984).

A second group is composed of extant species that either no longer inhabit the Balcones fault zone or are confined to small refugia in the canyons along the edge of the Edwards Plateau. Examples are *Sorex cinereus* (masked shrew), *Mustela erminea* (ermine), *Synaptomys cooperi* (southern bog lemming), *Microtus pennsylvanicus* (meadow vole), *Blarina brevicauda* (short tailed shrew), *Tamias striatus* (eastern chipmunk) and *Pitymys pinetorum* (pine vole). These species are found living today to the north or east in climates that are cooler and/or wetter than those in central Texas (Fig.3).

The third group of species still live in central Texas. Most of the vertebrate species living today in central Texas are found in Upper Pleistocene deposits in this area. Exceptions are

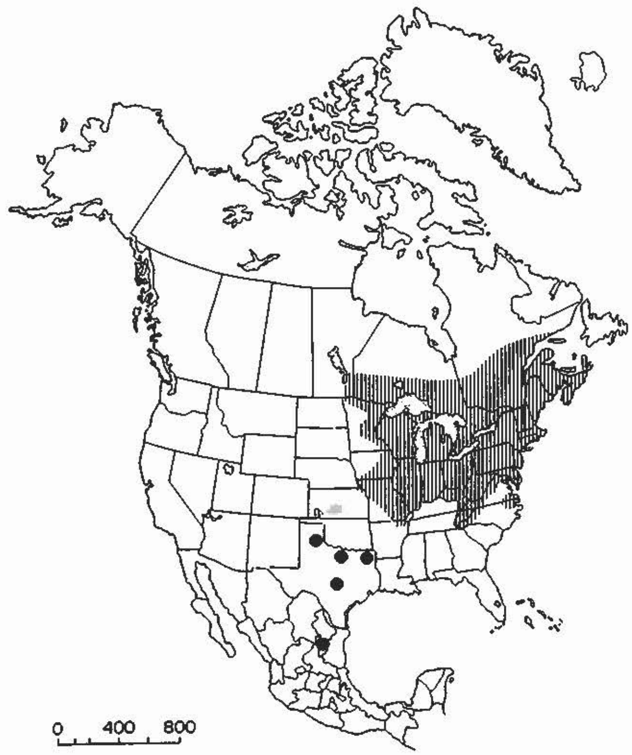

Figure 3. Map showing modern distributions of Synaptomys cooperi (vertical lines) and late Pleistocene occurrences in Texas and Mexico. Scale in miles.

Dasypus novemcinctus (nine- banded armadillo), Tayassu tajacu (collared peccary), Spermophilus variegatus (rock squirrel) and Bassariscus astutus (ringtail). The first two are recent arrivals [D. novemcinctus about 1890-1900 A.D.(Buchanan and Talmadge, 1954); T. tajacu somewhat earlier but probably after 1700 A.D.]. The precise time the latter two species appeared in central Texas is not known but it was some time in the Holocene.

The late Pleistocene faunas give information on Pleistocene environments. The use of extinct species for paleoenvironmental reconstructions is difficult because it is obviously impossible to obtain experimental or field data on their tolerances and habitat preferences. Data on close living relatives may not be applicable because of specific differences in habitat requirements.

Many of the extinct species were very widely distributed in North America, which can be interpreted either that these species had wide tolerances for environmental conditions or that a relatively uniform environment prevailed over North America during the Pleistocene. A detailed examination of the distributions of extinct species shows regional differences which almost certainly reflect regional environmental differences. The American mastodon (Mammut americanum) is much more abundant on the Gulf Coast Plain and in eastern North America generally, than on the Edwards Plateau or the High Plains. The mammoth (Mammuthus jeffersonii) on the other hand was common over most of Texas including the Gulf Coastal Plain. This difference in the relative abundance of mammoth and mastodon indicates differences in the environments of the two regions. The teeth of the two animals are quite different; those of the mammoth are complex and high crowned and better adapted to a diet of harsh vegetation such as grass than are the simple low crowned teeth of the mastodon. This indicates more forested areas on the Gulf Coastal Plain than on the Edwards Plateau. The mastodon was not completely absent from the Edwards Plateau but was probably restricted to stream valleys.

Other extinct species were either entirely or largely confined to the Gulf Coastal Plain. The long-nosed extinct peccary Mylohyus nasutus is confined to the eastern half of North America and is not known west of the Balcones fault zone. Extinct species that are either absent or rare west of the Balcones fault zone in addition to the long-nosed peccary, Mylohyus nasutus, are the ovibovine, Symbos cavifrons, which is common in the northeast and midwest and whose remains are frequently associated with woodland pollen (Semken et al, 1964), the large armadillo, Holmesina septentrionalis, which has one late Pleistocene record at Lubbock (Johnson, 1985), the glyptodont, Glyptotherium floridanus, with one late Pleistocene record from Andrews County (Lundelius, 1967), and a capybara, Neochoerus pinckneyi. All of these animals are associated to a considerable extent with forest or woodland conditions and some, such as the glyptodont and capybara, with permanent bodies of water (Gillette and Ray, 1981). The living relatives of Holmesina, Glyptotherium and Neochoerus are warm climate animals. Their southerly distribution suggests mild temperatures for the Gulf Coastal Plain during the late Pleistocene. Thus the distributions of many of the extinct forms provide information on Pleistocene environments.

Extant species in Pleistocene faunas are a more reliable source of paleoenvironmental data. Because there is little direct information on animal tolerances, present distributions are used as approximate indicators of their environmental requirements. Pleistocene faunas of central Texas have a number of species that do not live there today but are found to the north and/or east in areas with cooler and/or wetter climates.

The following species are found today well to the north of Texas. Sorex cinereus (masked shrew), known from several late Pleistocene faunas of central Texas including Cave Without A Name, is presently found throughout northern North America. Its southern limit on the Great Plains is southern Nebraska but it is found farther south at higher elevations in New Mexico, Tennessee and North Carolina. The southern bog lemming, Synaptomys cooperi, is known from Cave Without a Name in Kendall County. Its present distribution southwestward ends in central Missouri except for two outliers associated with artesian springs in southwestern Kansas. Microtus pennsylvanicus (meadow vole) whose southern limits are in central Nebraska and northern Missouri is known from Pleistocene faunas from Cave without a Name in Kendall County. The eastern chipmunk, Tamias striatus, is known from Friesenhahn Cave and Cave Without a Name (Graham, 1984). Its modern distribution covers most of the eastern United States with the exception of Florida and the Atlantic Coastal Plain.

The ermine, Mustela erminea and a large subspecies of raccoon, Procyon lotor simus, are also found in Pleistocene faunas of central Texas, the former from Cave Without a Name, the latter from Pleistocene deposits in Levi Shelter, Travis County and Holocene deposits in the Kyle Site, Hill County. Sorex cinereus is presently found in the northern part of North America including the Arctic. It, like Sorex cinereus, extends farther south in the Rocky Mountains into northern New Mexico and on the east coast into Maryland. Procyon lotor simus, which has much more massive mandibles and skulls than modern populations from central Texas is now confined to the Pacific Northwest (Wright and Lundelius, 1963).

Another group contains extant species that are no longer found in central Texas; these range to the north and/or east but do not extend as far north as those in the previous group. The prairie vole, Microtus ochrogaster, and the pine vole, Pitymys pinetorum, are difficult to separate on the basis of fragmentary material but both appear to have been present in Pleistocene faunas of central Texas. The southern short-tailed shrew, Blarina carolinensis, is found in many Pleistocene faunas (Cave Without a Name, Friesenhahn Cave and Laubach Cave). Another such species is the prairie dog, Cynomys ludovicianus, which is also represented in several late Pleistocene faunas (Friesenhahn Cave, Cave Without a Name, Laubach Cave). It is widely distributed today on the Great Plains but does not extend southeastward beyond Mason County. All of these extant extralimital species indicate a late Pleistocene climate that was cooler and probably had more available moisture than the present climate of central Texas.

Another characteristic of the Pleistocene faunas of this region is the association of species that are now allopatric and whose habitat requirements seem to be mutually exclusive. Hibbard (1960) called attention to this and proposed that these associations indicate a climate with less seasonality than the present. This is based on the assumption that the northern species are limited today to the south by the summer temperature maxima and their associated high evaporation rates. A comparison of the distribution maps of these species with the climatic maps of Visher (1945) support this hypothesis. Several of these species (Sorex cinereus, Mustela erminea) extend farther south in the Rocky Mountains and Appalachian Mountains than they do in the central part of the continent and Visher's maps show that both higher rainfall and lower temperatures extend farther south in these areas today than in the central part of the continent.

These associations have been termed "disharmonious" by Semken (1974) and "intermingled" by Graham (1985). All well known late Pleistocene faunas in central Texas show these associations. The following two examples are typical: Late Pleistocene faunas from Schultze Cave (Dalquest et al, 1969) and Friesenhahn Cave (Graham, 1976a) have both Cynomys ludovicianus (black-tailed prairie dog) and Tamias striatus (eastern chipmunk). These two species are today allopatric (Fig. 4). The Schultze Cave fauna also contains both Mustela erminea (ermine) and Reithrodontomys fulvescens (harvest mouse) also allopatric today (Fig. 5). They are an indication that the late Pleistocene climate of central Texas was different from any climate we see today and that there are no precise modern analogues. The Pleistocene faunas had a higher species density than do the modern ones. This is not only because of the presence of the extinct species, but also the mixing of extant northern and southern species contributed to the species richness (Foley, 1984; Graham, 1978, Guilday et al., 1978).

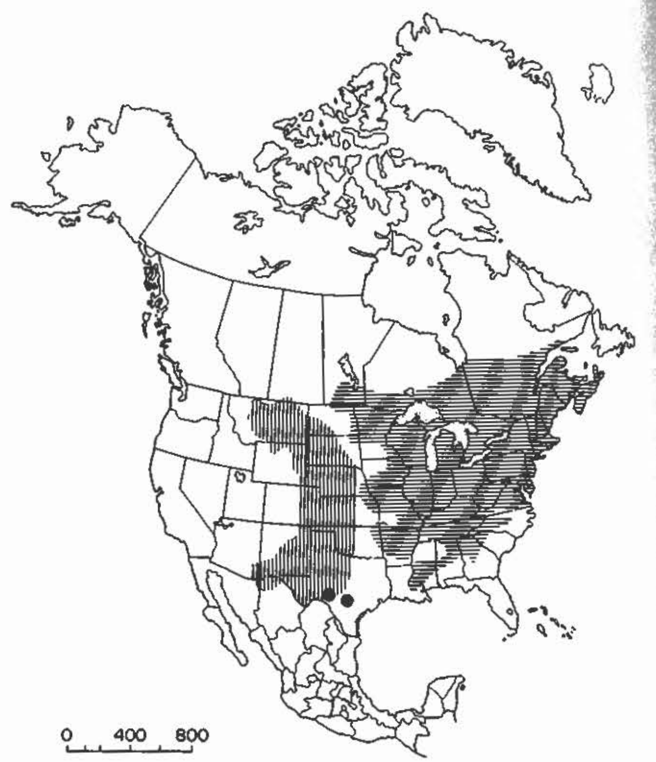

Figure 4. Map showing modern distributions of Cynomys ludovicianus (vertical lines) and Tamias striatus (horizontal lines) and the locations of Schulze Cave and Friesenhahn Cave (filled circles) where both occur in Pleistocene faunas. Scale in miles.

Extinction

The major biological event that marks the end of the Pleistocene was the extinction of many species of large mammals and a few species of small mammals. The exact number of species involved depends somewhat on the taxonomic arrangement used. Martin (1984) lists genera of large mammals (body weight < 44 kilograms) and genera of small mammals (body weight > 44 kilograms) that became extinct in North America at the end of the Pleistocene. A conservative estimate of the number of species involved is 28 large and 4 small mammalian species. The time of extinction has been investigated by means of radiocarbon dates by Jelinek (1957), Hester (1960) and Martin (1958, 1967, 1984). The lastest comprehensive study (Martin, 1984) involving new

Figure 5. Map showing the modern distributions of Mustela erminea (horizontal lines) and Reithrodontomys fulvescens (vertical lines) and the location of Schulze Cave (filled circle) where both occur in a Pleistocene fauna. Scale in miles.

dates and re-evaluation of many radiocarbon dates indicates that the majority of the species disappeared 10,000-11,000 years ago.

The cause or causes of this extinction have been discussed by many authors for decades. Martin (1967, 1973, 1984) has presented the case for human overpredation. Guilday (1967), Slaughter (1967), Axelrod (1967), Lundelius (1967), and Graham and Lundelius (1984) have argued that the climatic change that took place at the end of the Pleistocene was the primary cause. The case for human overpredation rests heavily on the close timing between the arrival of humans in North America and the disappearance of the large mammals. It assumes that the early human populations were numerous and were technologically capable of exterminating these species. The case for climatic change rests largely on the assumption that niches were eliminated by the climatic change. This hypothesis is supported by the disappearance of the disharmonious assemblages at the same time that the large animals became extinct.

Holocene Faunas and Climates

After the extinction of the large mammals 10,000-11,000 years ago, the fauna of central Texas consisted of the modern fauna plus a few species that are now found north and east of central Texas in areas of cooler and more mesic climates. A few species, such as the armadillo, arrived later in the Holocene.

Except for Procyon lotor simus, the species that are found today farthest north disappeared earliest from central Texas. Sorex cinereus, Microtus pennsylvanicus and Mustela erminea are last known from Cave Without a Name (10,900 yrs B.P.). They apparently disappeared from central Texas with the extinct fauna. Synaptomys cooperi is known from Miller's Cave associated with a radiocarbon date on bone of 7,300 yr B.P. This date should be regarded as a limiting date. The actual age is probably older as radiocarbon dates on bone tend to be somewhat young (Tamers and Pearson, 1965).

Another group of species that disappeared later are found today various distances from the Edwards Plateau. Microtus ochrogaster (prairie vole) which today does not occur south of Oklahoma was present at Miller's Cave in Llano County 3,000 years ago. Blarina carolinensis, now found in east Texas, was at Austin 1,000 years ago (Barton Road site) and possibly as recently as 600 years ago (Mac's Cave). A microtine rodent (either Microtus ochrogaster or Pitymys pinetorum) is also represented in the Mac's Cave deposits.

There is some evidence that Blarina carolinensis, Microtus ochrogaster and/or Pitymys pinetorum retreated eastward through time across the Edwards Plateau. Their latest occurrence in the western part of the Edwards Plateau is at Felton Cave in Sutton County 7,800 years ago. None are known from Holocene deposits of either Centipede or Damp caves in Val Verde County. This absence is significant because these caves, which have produced abundant small mammal faunas and are located along the canyon of the Rio Grande, would have been expected to be more mesic than the uplands.

The deep, mesic canyons along the dissected edge of the Edwards Plateau are refugia today for a number of organisms such as the sugar maple (Acer saccharum), a salamander (Plethodon glutinosus) and the pine vole (Pitymys pinetorium) whose primary distributions lie east and/or northeast of central Texas today (Blair, 1958). This is likely to have been the case for the entire Holocene during which species formerly widespread on the Edwards Plateau persisted as isolated populations for varying lengths of time in these locally favorable areas as the regional climate changed.

Several species, Geomys bursarius (plains pocket gopher), Scalopus aquaticus (eastern mole), and Cryptotis parva (least shrew) are now absent from most of the Edwards Plateau but occur to the north, south and east. The record of Geomys bursarius is the best of these and the restriction of its range seems to follow no pattern, geographic or chronologic. This, plus the fact that its modern distribution in central Texas is spotty and related to locally favorable soil conditions, suggests that soil erosion on the Edwards Plateau is responsible for its disappearance over much of the area. Remains of the pocket gopher have been found in very young deposits in this area which suggests that restriction of range due to soil erosion has been operative very recently and probably is still going on.

Mus musculus (house mouse), a European animal brought to North America by Europeans, has been found in the black fill unit at Longhorn Cavern in Burnet County indicating a date younger than 1700 A.D. (Semken, 1961). This unit also contains Geomys bursarius which does not live today in Burnet County. Its nearest occurrence is in Llano County approximately 40 miles away. The top twelve inches of a black soil unit in Rattlesnake Cave in Kinney County also contains both Mus musculus and Geomys bursarius. The nearest modern occurrence of G. bursarius is in Dimmit County 75 miles to the south. In both instances Geomys remains have been recovered from a black sediment similar to the soil found on the Edwards Plateau today. The record of the burrowing mole Scalopus aquaticus is similar but is less complete.

The species listed earlier as being absent from or sparsely distributed on the Edwards Plateau are fossorial and require a reasonable depth of soil. Their scarcity in this area today seems to be related to the generally thin soil. The stage was set for the removal of soil from the Edwards Plateau by the entrenchment of the streams during or before the Pleistocene. The process was probably accelerated by the post-Pleistocene change to drier conditions. The last stage in the removal of the topsoil from this area seems to have taken place since 1800 as the result of extensive overgrazing which destroyed much of the vegetation (Semken, 1961).

There is no evidence in the known Holocene faunas that the climate during the interval 4,000-6,000 years B.P. was any drier or warmer than at present as indicated by the occurrence of Lutra canadensis (otter) in the Wunderlich site in Comal County 5,000 years ago and the fauna from Centipede Cave in Val Verde County 5,000 years ago. This picture may be somewhat biased by the concentration of sites along the eastern and southern edges of the Edwards Plateau where erosion has opened many caves which are the source of much of the fossil material. Most of these caves are adjacent to canyons which maintained more moist environments than the uplands. Vertebrate fossils from more localities away from the canyons will be needed to settle this question.

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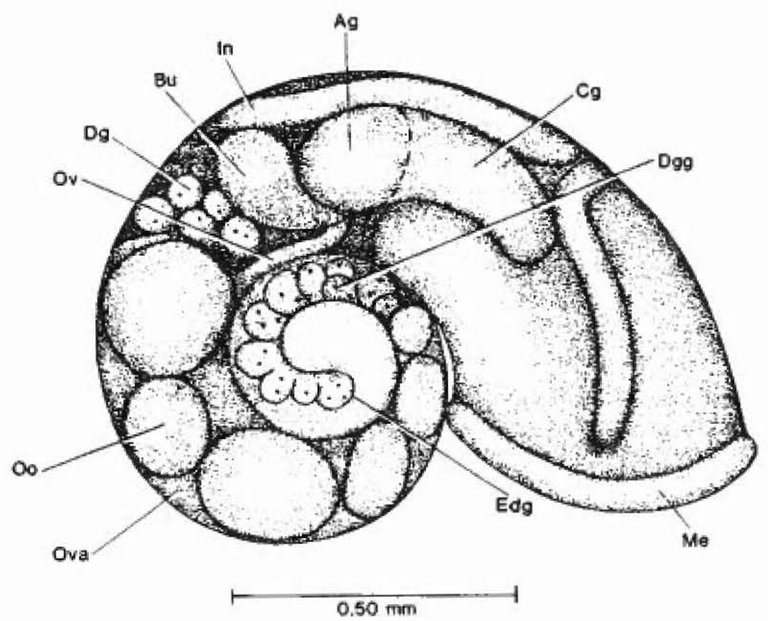

A SNAIL FROM THE EDWARDS AQUIFER.

Morphology of a female *Phreatodrobia nugax* (minus the head-foot), as seen from the right (and slightly dorsal) side. The kidney tissue is not shown. Ag = albumen gland; Bu = bursa copulatrix; Cg = capsule gland; Dg = digestive gland; Dgg = digestive gland granule; Edg = posterior end of digestive gland; In = intestine; Me = mantle edge; Oo = oocyte; Ov = oviduct; Ova = ovary.

THE BIOTA OF THE EDWARDS AQUIFER AND THE IMPLICATIONS FOR PALEOZOOGEOGRAPHY

Glenn Longley
Edwards Aquifer Research & Data Center
Southwest Texas State University
San Marcos, Texas 78666

ABSTRACT

The Edwards Aquifer is home to a very diverse assemblage of forty, highly adapted, aquatic, subterranean described species. Several additional invertebrate species have been discovered, but have not yet been described. The most unusual of the species are blindcatfish existing more than 600 m beneath the land surface. Possible explanations regarding the existence of this community include marine organisms adapting to the aquifer from a time when paleokarstification occurred and the caves were then inundated in a marine situation similar to that today in Bermuda. Some organisms may have entered the aquifer during the Miocene when extensive faulting occurred along the present Balcones Escarpment. Finally some organisms may have entered the aquifer through spring openings to escape the colder surface temperatures during the ice ages. The paleogeographic implications of the diverse fauna are astounding.

INTRODUCTION

The unusually diverse subterranean aquatic community of the Edwards Aquifer poses some interesting questions regarding its origin. There have been a total of 40 species described from the aquifer - Table 1 (Hershler and Longley, 1986). The two most diverse groups in the faunal assemblage are the crustacean, gammarid amphipods and the gastropod, hydrobiid snails. In both groups there are species apparently derived from both marine and freshwater ancestors. This diversification would have logically occurred since the Cretaceous period. The major question posed by these species occurrence in the deep confined aquifer is how did they get there. The zoogeographic and ecological implications are considerable.

The Edwards (Balcones Fault Zone) Aquifer. The aquifer extends for 282 km from Brackettville to Salado (Fig. 1). Within the aquifer, areas below the Balcones Escarpment are confined (artesian) and those above are typically unconfined (water table). The large size and the amount of cavernous porosity in the confined region of the aquifer makes this aquifer one of the worlds most unique karst aquifers. The deposition of the Edwards formation began almost 100 million years ago. The deposition occurred in a shallow sea with a variety of environments from tidal flats to coral reefs. The area may have been similar to shallow areas in the Bahama islands today. The early limestones were alternately submerged and then exposed allowing early formation of cavernous porosity. It is possible that caverns similar to those in Bermuda that connect Blue Holes to caverns inland may have formed. In time all of Central Texas was covered by a deep Cretaceous sea. Many hundreds of feet of sediments were deposited over this early aquifer. As the North American continent was slowly uplifted the Cretaceous seas receded. Rivers formed that cut across the overlying sediments again gradually exposing the underlying Edwards with its cavernous porosity.

By the Miocene another major event in the history of the Edwards Formation occurred (12 - 17 million years ago). This was a period of extensive faulting resulting in the Balcones Fault Zone concurrent with subsidence in the Gulf of Mexico area. The formations dipped toward the present day Gulf coast. The faults allowed new movement of groundwater in the Edwards, in some areas acting as recharge points, and in others as resurgence points (springs). Further solutioning continued with enlargement of the cavernous porosity along the fault zone. The large major geologic event that may have ultimately influenced the biological composition of the aquifer began with the onset of the ice ages some three million years ago. The brief synopsis of the history of the Edwards will relate to when organisms of the various groups represented there may have first colonized the Edwards Aquifer.

DISCUSSION

The two most diverse groups represented in the aquifer are amphipod crustaceans and prosobranch gastropods. Most of the discussion will center on these two groups. The vertebrate fauna is also very interesting.

AMPHIPODS

Information obtained from samples of an artesian well on the Southwest Texas State University campus indicate that both in numbers of genera and species the subterranean amphipod diversity far exceeds any other groundwater community studied in North America.

The family Crangonyctidae is restricted to the Holarctic region and is believed to have originated on the old Laurasian landmass prior to the separation of North America and Eurasia in the Jurassic (Holsinger, 1978). The crangonyctids are allied morphologically at the superfamily level with several families living on landmass remnants of Gondwanaland in the Notogaean region. The crangonyctids are therefore believed to be an ancient group that was probably present in North American freshwaters prior to the Cretaceous. Since the Edwards Aquifer is developed in Cretaceous age limestones, the presence of Stygobromus there would imply that members of this genus have invaded and colonized subterranean water in this part of North America since the Cretaceous.

It is presumed that the invasions were by ancestral immigrants from a part of the continent that remained above the marine waters during late Mesozoic times.

in Abbott, Patrick L. and Woodruff, C.M., Jr., eds., 1986, The Balcones Escarpment, Central Texas: Geological Society of America, p. 51-54

Table 1. Described biota of the Edwards Aquifer.

- Platyhelminthes
  - Kenkiidae
    - Sphalloplana mohri Hyman
- Mollusca
  - Hydrobiidae
    - Phreatodrobia micra (Pilsbry & Ferriss)
    - Phreatodrobia nugax nugax (Pilsbry & Ferriss)
    - Phreatodrobia nugax inclinata (Hershler & Longley)
    - Phreatodrobia rotunda (Hershler & Longley)
    - Phreatodrobia conica (Hershler & Longley)
    - Phreatodrobia plana (Hershler & Longley)
    - Phreatodrobia imitata (Hershler & Longley)
    - Phreatodrobia punctata (Hershler & Longley)
    - Balconorbis uvaldensis (Hershler & Longley)
    - Stygopyrgus bartonensus (Hershler & Longley)
- Arthropoda
  - Cypridae
    - Cypridopsis vidua obesa Brady & Robertson
  - Cyclopidae
    - Cyclops cavernarum Ulrich
    - Cyclops learii Ulrich
    - Cyclops varicans rebellus Lilljeborg
  - Entocytheridae
    - Sphaeromicola moria Hart
  - Asellidae
    - Lirceolus smithi (Ulrich)
    - Asellus pilus Steeves
    - Asellus redelli
  - Cirolanidae
    - Cirolanides texensis Benedict
  - Monodellidae
    - Monodella texana Maguire
  - Crangonyctidae
    - Stygobromus flagellatus (Benedict)
    - Stygobromus russelli (Holsinger)
    - Stygobromus pecki (Holsinger)
    - Stygobromus balconis (Hubricht)
    - Stygobromus bifurcatus (Holsinger)
  - Hadziidae
    - Texiweckelia texensis (Holsinger)
    - Texiweckelia insolita Holsinger
    - Texiweckelia samacos Holsinger
    - Allotexiweckelia hirsuta Holsinger
  - Bogidiellidae
    - Parabogidiella americana Holsinger
  - Artesiidae
    - Artesia subterranea Holsinger
  - Sebidae
    - Seborgia relicta Holsinger
  - Palaemonidae
    - Palaemonetes antrorum Benedict
    - Palaemonetes holthuisi Strenth
  - Dytiscidae
    - Hadeoporus texanus Young & Longley
- Chordata
  - Ambystomidae
    - Typhlomolge rathbuni Stejneger
    - Typhlomolge robusta Longley
  - Ictaluridae
    - Satan eurystomus Hubbs & Bailey
    - Trogloglanis pattersoni Eigenmann

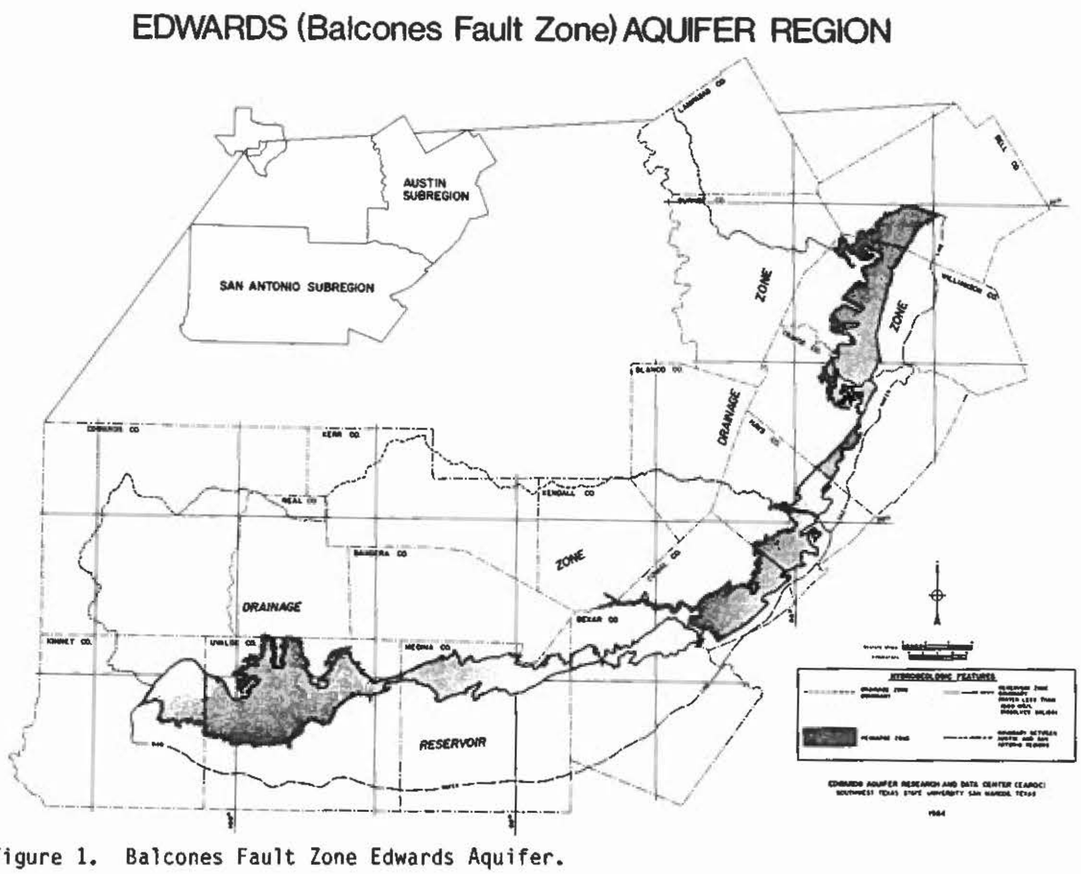

Figure 1. Balcones Fault Zone Edwards Aquifer.

The family Hadziidae are part of a group that is composed of species that inhabit marine, brackish or freshwater habitats, largely in temperate or tropical regions. Many are found in the old Tethys Sea region (ie., the greater Caribbean and Mediterranean regions in particular). All freshwater species are troglobites or phreatobites. Closely related subterranean hadziid genera also occur in brackish and freshwater habitats in the Mediterranean region, in shallow marine and anchialine habitats at a few spots in other tropical oceans. The genera occurring in the Edwards were probably derived from marine and/or brackish water ancestors at various times from the late Cretaceous to the late Tertiary (Holsinger, 1974). These forms were probably relicted during the recession of marine waters in the late Cretaceous.

The family Bogidiellidae is part of a larger complex of the superfamily Bogidielloidea. The majority of species are recorded from the greater Caribbean and Mediterranean regions. Ruffo (1973) and Stock (1977, 1978) have made strong cases for the evolution of freshwater members of Bogidiellidae from marine ancestors, with freshwater invasion occurring at different places over a long period of time.

The family Artesiidae is known only from the Edwards Aquifer. Its probable affinity with Bogidiellidae makes it likely that this family had a marine origin, with ancestral forms relicted in freshwater following the Cretaceous embayment of central Texas.

The family Sebidae, which is predominately marine, are small, weakly pigmented, mostly eyeless species from benthic habitats. Due to their characteristics, this group would have been good candidates for colonization of interstitial freshwater habitats during marine transgressions. The presence of species in a land-locked, oligohaline-brackish water lake in the Renell Islands of the South Pacific, assumed to have been isolated there since the Late Pliocene (Bousfield, 1970), may indicate the manner in which the ancestors of the Edwards Aquifer form became isolated in, and adapted to, the transitional aquatic environment of south-central Texas during recession of sea water in the late Cretaceous or early Tertiary.

GASTROPODS

The Hydrobiidae (Rissoacea) are a large family (over 100 genera and 1000 species; Davis, 1979) of dioecious, gill-breathing snails that have radiated into diverse fresh- and brackish-water habitats worldwide. Minute, unpigmented hydrobiids occupy groundwater habitats in numerous areas, with a large fauna occurring in karst regions of Europe, lesser numbers occurring in North America, Mexico, Japan, and New Zealand (Hershler and Longley, 1986). Little is known of the zoogeography of these taxa, in large part due to their small size (often less than 2 mm) and the difficulties in sampling their habitat. The described species of the Edwards Aquifer have been found in 14 artesian wells and four springs. The wells that yielded snails ranged in depth from 59 - 582 m. All of these wells are cased and there is no doubt that the snails were expelled from the deep artesian zone. Their habitat probably includes fractures, joints and caverns in the Edwards formation. It is also possible, given their small size, that they even inhabit interstices.

OTHER INVERTEBRATES

In samples of wells in the San Antonio area, some specimens of a Foraminiferan from the family Lagenidae were found. They appear to be fresh not fossil forms. They were tentatively identified as a species of Robulus. For identification Cushman, 1928 was used. Vandel, 1965 discusses a discovery of A.L. Brodsky of an abundant population of Foraminifera in some wells in the Kara-Kum desert in the Trans-Caspian Province. The wells were about 20 m deep and were fed by slightly brackish ground water. Further work has not been done on the San Antonio forms, but will be completed in the future.

The only known North American Thermosbaenacean, **Monodella texana**, is found from the Edwards Aquifer. This representative of the family Monodellidae is most closely related to species that occur around the Mediterranean and West Indies (Stock and Longley, 1981). The species found in the Mediterranean region are all freshwater including groundwater forms. The absence of marine Thermosbaenacea in the Mediterranean may be explained by events in the late Miocene hydrographic history of that basin. The sea level dropped considerably and much of the remaining water was temporarily transformed into brine. Conceivably the marine ancestors became extinct in the Mediterranean during the late Miocene. In the West Indies, where no such drastic salinity change took place, marine Thermosbaenacea did survive. It is likely that ancestors of this species also entered the Edwards aquifer during a time when central Texas was a marine area.

Troglobitic isopods in the freshwater Asellidae and predominantly marine Cirolanidae show contrasting patterns of distribution and speciation. Asellids are derived from an ancient Holarctic group probably already established in freshwater prior to the breakup of Laurasia (Barr and Holsinger, 1985). Few cirolanid isopods live in fresh water, most of them are troglobites. Species from Bermuda, the Bahamas, and Aruba occur in anchialine waters; the remainder inhabit freshwater habitats in Texas, Virginia, Mexico, and several West Indian islands. Except for the species in the Bahamas, which were probably derived from marine ancestors by direct dispersal, most cirolanids appear to have originated by stranding during regression of marine embayments or through uplifting.

The shrimp of the family Palaemonidae were probably derived from ancestral forms that gave rise to the forms found in the aquifer and Texas estuaries today.

VERTEBRATES

Longley, 1978 discusses the status of two troglobitic salamanders occurring in the groundwaters of the San Marcos area. The species **Typhlomolge rathbuni** and **Typhlomolge robusta** are highly adapted neotenic species of the family Plethodontidae. They are considered the amphibians most adapted to cave existence in the world. They reproduce while retaining their gills, a larval characteristic. They have long legs with little musculature, an obvious adaptation to their total aquatic existence.

Two species of blind catfish of the family Ictaluridae occur in the groundwaters of the San Antonio area. They are highly adapted species having no airbladders, unlike their surface relatives. One species, the Toothless blindcat, Trogloglanis pattersoni has a suckerlike mouth on the underside of its head unlike any other member of the family. The fish are found in outflow from wells that penetrate the Edwards formation between 402 m at the Artesia well and 582 m at the O.R. Mitchell (now S. Kleburg) well. These are flowing artesian wells having considerable artesian pressure (Longley and Karnei, 1979). Considering the amount of change in these species when compared to other species in their families it seems logical to postulate that they found their way into the aquifer in prepleistocene times perhaps as a means of escaping the colder temperatures on the surface. The temperatures of the groundwater tend to remain constant and would naturally dampen the effects of periods of extreme cold, an advantage to these fish. The same type of retreat into springs and then further down in caves was probable for all of the vertebrates in the aquifer.

SUMMARY

The unique community of aquatic subterranean forms inhabiting the Edwards Aquifer raise many questions regarding their origins. Additional study is needed to relate marine relict species occurrences in this system. When adequately sampled, other aquifer systems, such as the Floridean Aquifer, will possibly show similar relationships.

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EARLY HUMAN POPULATIONS ALONG THE BALCONES ESCARPMENT

Thomas R. Hester
Center for Archaeological Research
The University of Texas at San Antonio
San Antonio, Texas 78285

ABSTRACT

Evidence of prehistoric human habitation of the Balcones Escarpment region of Texas can be traced to at least 11,000 years ago. The cultural chronology of the Balcones Escarpment is divided into three major prehistoric periods: Paleo-Indian, Archaic, and Late Prehistoric. A brief overview of this cultural sequence is provided. However, the paper focuses on the early occupations of Paleo-Indian times. Some paleontological sites, such as Friesenhahn Cave, have yielded chipped chert flakes suggestive of even earlier occupation, but the situation is certainly not resolved at this time. Other sites have associated human artifacts and late Pleistocene fauna; at others, fluted points, such as Clovis and Folsom, are indicative of great antiquity. The latter part of the Paleo-Indian period, in the early Holocene, presents some interpretative problems that are discussed here.

Continuing archaeological investigations in this region, particularly large survey and excavation programs, need the participation of geomorphologists. Through interdisciplinary collaborative research, a better job can be done of locating deeply buried Archaic and Paleo-Indian sites. Geomorphologists can contribute to the interpretation of site deposit formation and can address the problem of ancient climatic patterns that may be revealed in gravel deposits at some sites.

INTRODUCTION

The focus of this paper is on the archaeology of the Balcones Escarpment area of south-central Texas, and especially on those sites that can be dated to late Pleistocene-early Holocene times. First a summary is provided of the prehistoric cultural chronology that has been established for this area, and then the earliest sites found in this chronology are reviewed. For purposes of geographic control, most of this discussion is confined to those counties along the southern and southwestern edge of the Edwards Plateau--the area traversed by the Balcones Escarpment (Fig. 1). These include the counties of (from west to east) Kinney, Uvalde, Medina, Bexar, Comal, Hays, Travis, and Williamson. It is fortunate that a considerable amount of archaeological research has been done in several of the counties, both on the escarpment and below it.

AREA CULTURE HISTORY

Archaeologists have defined four broad periods of prehistoric human occupation in this area: Paleo-Indian, Archaic, Late Prehistoric, and Historic. These span some 11,000 years.

Paleo-Indian

Texas archaeologists use this term to refer to the earliest human occupation of the state, roughly 9200-6000 B.C. The initial part of the period encompasses the late Pleistocene. Both occupation and kill-sites, with associated human artifacts and Pleistocene fauna, have been identified along the Balcones Escarpment. While the dating of the onset of the Holocene remains somewhat ambiguous in the evaluation of many of these sites, it is clear that stylistic and technological traits of the projectile points of the early phase of the Paleo-Indian continue into late Paleo-Indian times. We assume that population size, settlement patterns, and a highly mobile lifeway likewise characterize the Paleo-Indian cultural pattern as late as ca. 6000 B.C.

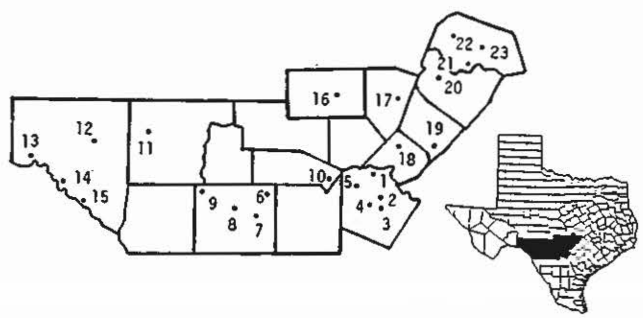

Figure 1. Locations of Selected Archaeological Sites Along the Balcones Escarpment. 1, Friesenhahn Cave; 2, Panther Springs site (41BX228); 3, St. Mary's Hall (41BX229), and Granberg II (41BX271); 4, Orchard site (41BX1); 5, 41BX52; 6, La Jita site (41UV29); 7, Kincaid rockshelter; 8, Leona Watershed; 9, Montell rockshelter; 10, 41BN63; 11, Schulze Cave; 12, Baker Cave; 13, Bonfire rockshelter; 14, 41VV162A; 15, Devil's Mouth site; 16, Gamenthaler site; 17, Wheatley site; 18, Canyon Reservoir (Wunderlich site); 19, Spring Lake site; 20, Levi rockshelter; 21, Wilson-Leonard site; 22, John Ischy site; 23, Rowe Valley site.

While Paleo-Indian sites with clear evidence of Pleistocene faunal associations are few, the projectile points that characterize the early part of this period (9200-8000 B.C.) are widespread; these include Clovis, Folsom, and Plainview points (Fig. 2). Similarly, the later phase diagnostics are quite common, even though in situ, stratified components are infrequent. These diagnostic point types are: Golondrina, Scottsbluff, Angostura (Fig. 2), and some highly localized styles still under analysis (e.g. Barber points; see Turner and Hester, 1985, for further illustrations and discussions of all these types).

in Abbott, Patrick L. and Woodruff, C.M., Jr., eds., 1986, **The Balcones Escarpment, Central Texas:** Geological Society of America, p. 55-62

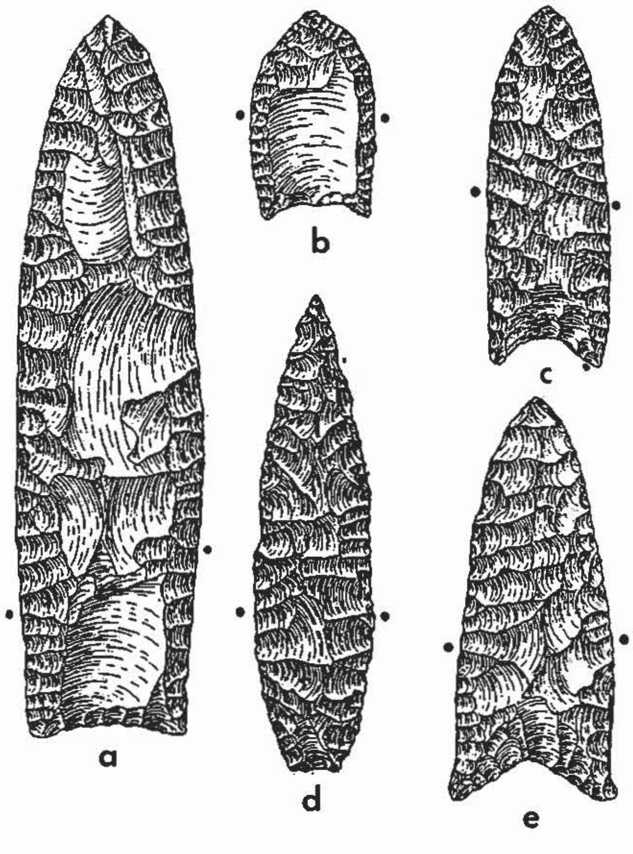

Figure 2. Paleo-Indian Point Types. a, Clovis; b, Folsom; c, Plainview; d, Angostura; e, Golondrina. Dots indicate extent of edge dulling (related to hafting techniques). Length of a, 126 mm. Drawings from Turner and Hester 1985.

Archaic

The term "Archaic" is used to denote a long time span of hunting and gathering cultural patterns that began around 6000 B.C. and continued until 800 A.D. The period is broken up into several subperiods, largely on the basis of changes in projectile point styles, along with shifts in settlement patterns, other lithic tool forms, use of certain plant and animal resources, and the like. Some areas of the Edwards Plateau are better known than others due to intensive archaeological research in those areas. For example, Prewitt (1981) has defined a tightly controlled chronological sequence for the Travis, Williamson, and Bell Counties area (see also Sorrow and others, 1967), but it cannot be applied in all areas of the Edwards Plateau--the "central Texas archaeological area." It is clear that other sections of this vast region share some similarities to Prewitt's sequence, but manifest--as we would expect from human cultures--localized differences (e.g. Black and McGraw, 1985).

A recent overview of the Archaic chronology of the region has been written by Black (n.d.). It is based in part on chronological data from the Balcones Escarpment zone, from sites such as 41BX228 (Panther Springs; Black and McGraw, 1985), La Jita (Hester, 1971), and the Canyon Reservoir sites (Johnson and others, 1962), and builds on other summaries of local chronology (e.g. McKinney, 1981; Story, 1985).

The <u>Early Archaic</u> (6000-3000 B.C.) is typified by specific diagnostic dart point types (Bell, Gower, Early Corner-Notched, etc.; Fig. 3) and tool forms (Guadalupe and Clear Fork implements). It is suggested that population densities were low and groups were organized into small, highly mobile bands. Interestingly, many of the key sites of this era are clustered along the edge of the Balcones Escarpment. Both McKinney (1981) and Story (1985) have speculated that this phenomenon might be related to a greater availability of water resources in this physiographic area, during a hypothesized arid climatic episode in the Early Archaic times.

An important Early Archaic site is Granberg II (41BX271) along Salado Creek in northern Bexar County (Hester, 1980). Excavations were directed there in 1979 by this author. In a 3-meter excavation profile exposed at the site, Glen L. Evans (Markey, n.d.) noted that the lower 2.4 meters consisted of alternating gravel strata attributable to flood deposits, point bar formation, and heavy erosion. Early Archaic materials are mixed within these deposits. Further studies of the Salado Creek gravels may one day give us a better idea of climatic fluctuations on the edge of the Balcones Escarpment (see Black and McGraw, 1985).

The <u>Middle Archaic</u> (3000-1000 B.C.) is clearly a period of population increase, with the native peoples developing specialized adaptations to the hunting and gathering of abundant regional food resources--especially acorns and white-tailed deer. The Pedernales dart point type is a diagnostic of the period (Fig. 3), as are large accumulations of fire-cracked rock known as "burned rock middens." These

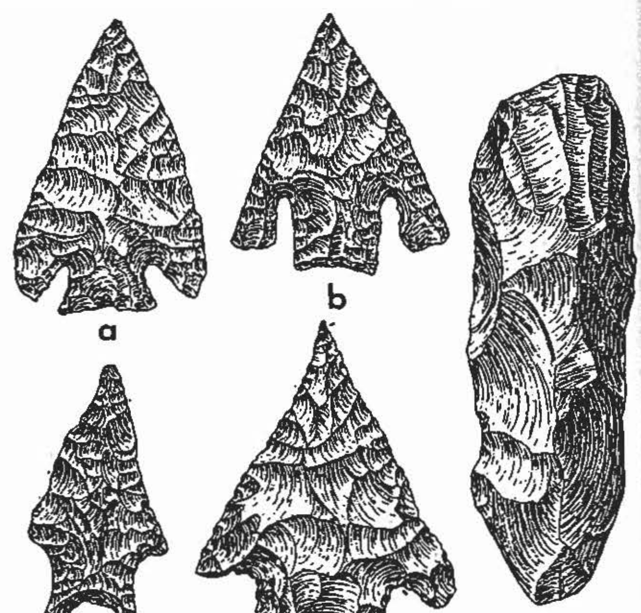

Figure 3. Archaic Artifacts. a, Early Corner Notched; b, Bell; c, Gower; d, Pedernales; e, Guadalupe tool. a-c,e, are from the Early Archaic; d, dates to Middle Archaic times. Length of e, 93 mm. Drawings from Turner and Hester 1985.

apparently represent intensive utilization of acorns, with the burned rock deposits indicative of certain kinds of processing (e.g. removing tannic acids from the acorns) and food preparation (perhaps stone-boiling in baskets of acorn mush, and roasting platforms of stone for cooking acorn bread and deer meat). These sites are very common throughout the Balcones Escarpment. Among the published burned rock midden sites of the Middle Archaic along the escarpment are La Jita (Hester 1971; see also Hester, 1970) and the Leona Watershed site (all in Uvalde County; Lukowski, in press), 41BN63 in Bandera County (Hester, 1985), Panther Springs in Bexar County (Black and McGraw, 1985), Wunderlich in Comal County (Johnson and others, 1962), and John Ischy in Williamson County (Sorrow, 1968).

The <u>Late to Terminal Archaic</u> (1000 B.C.-A.D. 800) represents a continuation of the hunting and gathering patterns of the Archaic, with some researchers seeing less specialization, but others noting evidence of bison-hunting in certain areas and the presence of cemetery sites (Black n.d.). Clearly, in some areas of central Texas, there may have been a trend toward territoriality and the development of wide-ranging trade contacts. Just south of the escarpment, in northern Bexar County, site 41BX1 (the Orchard site; Lukowski, 1986) represents one of these cemetery sites containing Gulf coast marine shell artifacts as grave goods.

Late Prehistoric

Between ca. 800 A.D. up to the advent of Europeans in the region, archaeologists see some distinctive changes in material culture and other facets of the long-lived Archaic hunting and gathering lifeway and have termed this part of the chronological framework the "Late Prehistoric" (Hester, 1971, 1980; earlier researchers used the term "Neo-American" [cf. Johnson and others, 1962], and the term "Neoarchaic" has also been proposed [Prewitt, 1981]).

The early part of this period is the Austin Phase, from ca. 800 A.D. to ca. 1200 A.D. It is at this time that the bow and arrow is first introduced into central Texas to replace the spearthrower or <u>atlatl</u> of Archaic and Paleo-Indian times. Along the Balcones Escarpment, there appears to have been a heavier use of rockshelters as occupation sites during this period (Harris, 1985); elsewhere, another trait of the Austin Phase seems to have been the use of cemeteries for disposal of the dead (Prewitt, 1974).

The latter part of the Late Prehistoric is termed the Toyah phase. Beginning around 1200 A.D. and apparently lasting up to about the time of historic contact, this cultural pattern emphasized bison-hunting. Dillehay (1974) has postulated a period of peak bison population in the southern Plains at this time. The herds spread into central and southern Texas (as far south as Alice, Texas around 1400 A.D.; Black, 1986) and we see a distinctive archaeological assemblage left behind by the peoples who hunted these animals. Thus far, no large kill-sites are known from this period, but there is a lot of bison bone in the campsites. Diagnostic artifacts include Perdiz arrow points, diamond-shaped beveled knives, a plainware pottery, and scrapers and perforators related to the processing and preparation of bison hides (Fig. 4). Major Toyah phase sites along the Balcones Escarpment include La Jita in Uvalde County (Hester, 1971), Panther Springs in Bexar County (Black and McGraw, 1985), Wheatley in Blanco County (Greer, 1976) and Rowe Valley in Williamson County. The peoples of the Toyah Phase may be the ancestors of the historic Tonkawa Indians of central Texas, but this has not been clearly established; work of the sort being done by Elton R. Prewitt at the Rowe Valley site may help to resolve the issue.

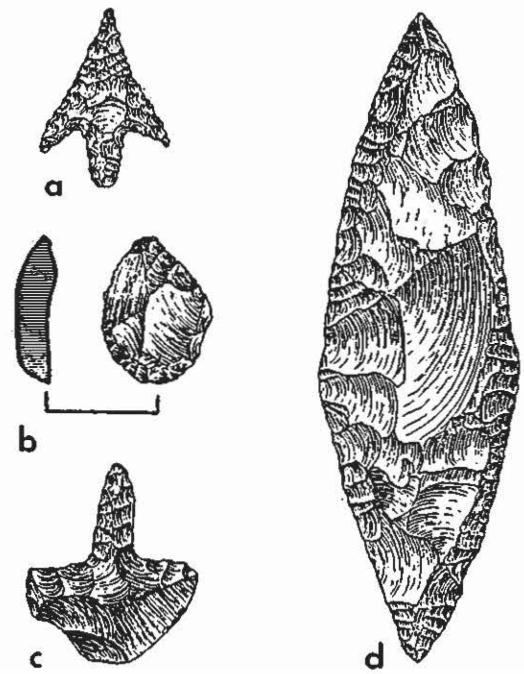

Figure 4. Late Prehistoric Artifacts. a, Perdiz arrow point; b, end scraper (cross-section is shown); c, perforator; d, beveled knife. Length of d, 113 mm. Drawings from Turner and Hester 1985.

Historic

Historic Indian sites in central Texas are extremely rare, usually represented by the occurrence of glass trade beads, native-made gunflints, and metal projectile points. The Tonkawa are presumed to be the historic natives of the region (Newcomb, 1961), but the pressures of the Spanish mission system, along with the incursions of outside groups, such as the Lipan Apaches and later the Comanches, all served to disrupt native lifeways in the area by the mid-18th century. This was long before any sort of anthropologically-oriented studies could be done.

PALEO-INDIAN SITES OF THE BALCONES ESCARPMENT

Current information on major Paleo-Indian sites along the Balcones Escarpment is summarized here. Some very important sites found in recent years remain unpublished and detailed data are not available. Some of the site summaries below have been adapted from Hester (n.d.). Sites of the Paleo-Indian period will be examined in their rough chronological sequence, from earliest to latest--although in some sites, such as Kincaid Rockshelter and the Wilson-Leonard site--there is considerable chronological overlap.

Early (and Possibly Early) Paleo-Indian Sites

In this part of the paper, several sites of Clovis and Folsom age in the Balcones Escarpment zone are discussed. In addition, there are some sites in the area that may be "pre-Clovis" in age and these will also be reviewed.

Friesenhahn Cave is located in northern Bexar County (Fig. 1). It is one of the most important late Pleistocene vertebrate fossil localities in Texas. First excavated in 1949 and 1951 (Evans, 1961), it was re-opened in the early 1970s (Graham, 1976). It is a site with a vertical entrance opening into an underground chamber (about 30 feet below the surface) that is 60 feet long and 30 feet wide. The cavern formed in limestone, and small stalactites and dripstone have developed in the chamber; stalagmites, fallen from the roof, are found buried in the fill. The deposits in the chamber are more than 10 feet thick, and contain abundant faunal remains which first began accumulating around 20,000 B.P., with the latest fauna incorporated in sediments 8,000-9,000 years old.

In the paleontological excavations first conducted by the Texas Memorial Museum under the direction of Glen L. Evans, and later carried out by Russell Graham of the Department of Geology at The University of Texas at Austin, a number of pieces of chert (flint), shell, and bone were found which bear some suggestion of human modification. Most attention has focused on the lithics. Most of these are small pieces of chert, and a few have chipping along the edges. Opinions vary widely as to whether or not these are indeed artifacts. Evans, the original excavator, felt they were not. This opinion was shared by Irwin (1971) in a review of early human cultures in the western United States. Taking opposite positions were Sellards (1952, Fig. 43), Wormington (1957), Jennings (1974) and others, who consider at least a few of the chert pieces to be stone tools.

Graham's more recent work at the cave has shed light on the problem. More pieces of chert were unearthed and could be sorted into the two main phases of sediment accumulation. Those from the earliest phase, between 20,000 and 17,000 years ago, remain enigmatic. Some have chipped edges, but it is impossible to tell whether these are artifacts or the result of natural modification. The uplands of northern Bexar County contain extensive chert exposures and naturally modified chert flakes abound. Taken out of context, some of them could be misidentified as artifacts. The only definite artifact identified from Friesenhahn Cave as a result of Graham's work comes from the late sediments (his "modern sediments") dating to 8,000-9,000 years ago. This is well within the known range of distinctive human occupations in the region. A modified mussel shell fragment also comes from this context, along with bones that were apparently butchered or altered by man. It is still unclear as to whether these few items represent human use of the cave or whether these are objects washed into the cave from the surrounding area.

It is my opinion, and one that is shared by the excavators, that "pre-Clovis" artifacts are absent from the early deposits at Friesenhahn. Later human cultural materials, possibly referable to late Paleo-Indian times (or at least that general time frame) are found in the later sediments.

At Schulze Cave in Edwards County, Walter Dalquest and others (1969) report three human teeth associated with Pleistocene mammalian fauna which they dated at about 20,000 years B.P. The site was dug by paleontologists, and the finds have not been studied either by physical anthropologists or archaeologists, and thus we must await further data in order to properly evaluate it.

Montell Rockshelter, in Uvalde County (Fig. 1), has Pleistocene fauna at the base of its deposits, and when excavated by Glen Evans in 1947, some human artifacts including a Lerma point were found in a stratum overlying the fauna. Evans (pers. comm., 1978) is of the opinion that no artifacts were associated with the extinct mammals.

Levi Rockshelter, a stratified site near Austin, Texas, was excavated in the early 1960s by H. L. Alexander, Jr. Additional work was undertaken by Alexander and his students in fall, 1977. In the earlier work (Alexander, 1963), an occupation zone was reportedly found below a stratum containing a "possible Clovis point and a Plainview point ... associated with bones of Equus sp and Platygonus sp." (p. 510); it was dated at 10,000 years ago. Found in the lower zone were a scraper, two utilized flakes, and a chopper, along with the remains of dire wolf and tapir. Since the culturally-mixed overlying zone is radiocarbon dated at ca. 8000 B.C., well after the end of the Clovis horizon, it is debatable as to whether or not these earlier materials represent primary associations.

Alexander (1982) has briefly described the results of the 1974 and 1977 excavations at the Levi site. He ascribes a number of stone tools and flakes to his Zone I ("pre-Clovis"), along with bone tools (Alexander, 1982, Fig. 6.5). Extinct tapir, dire wolf and bison species are reported, along with a variety of fauna (small mammals, rodents, reptiles, birds) still present in the area today. Efforts to obtain absolute dates on Zone I have thus far not yielded any results which the excavators consider satisfactory. Further publication of the 1974 and 1977 data is awaited before a full evaluation can be made of the Levi materials.

In Uvalde County in south-central Texas, along the edge of the escarpment, the Kincaid Rockshelter has yielded Pleistocene fauna (horse, elephant, bison, large cat) from beneath a man-laid cobble pavement probably of Folsom horizon times. Atop the pavement, in Zone 4, were chipped stone artifacts, along with late Pleistocene vertebrate fossils, especially bison. The tools included lanceolate bifaces, flakes with utilized edges, a graver tool, several flake cores, and 52 pieces of flake debris. Also found was the basal fragment of an obsidian projectile point. This specimen has been linked by trace element analysis (neutron activation analysis) to geologic sources near Queretaro, Mexico, about 1000 km from Kincaid Rockshelter (Hester and others, 1985). This artifact and the other materials in Zone 4 are thought to date prior to 10,000 years ago. The excavator, Glen L. Evans, along with T. N. Campbell, have prepared a lengthy manuscript on the site, but this has not yet been published. Three Folsom points were found by relic-collectors at the site, and while no in situ specimens of this type were found in the 1948 and 1953 excavations, Evans (pers. comm. 1978) believes they were likely from Zone 4.

Folsom points, and possibly those of the Clovis type, were found in excavations at site 41BX52 in northern Bexar County in 1979. The investigations, conducted by archaeologists from the State Department of Highways and Public Transportation, recovered the fluted points, scrapers, and other materials from this open campsite. No Pleistocene faunal remains were found. At present, the archaeologist in charge of report preparation, Jerry Henderson (pers. comm. 1986), indicates that there may have been a Clovis occupation at the site, with an overlying, and much larger, Folsom habitation area. Analysis is still in the early stages.

At San Marcos, on the edge of the escarpment, Shiner (1983) has reported Clovis and other Paleo-Indian points from underwater investigations at the Spring Lake site. This site, inundated by a 19th-century dam on the San Marcos River, was apparently situated at or near ancient springs. This has led Shiner (1983) to suggest that Clovis and later Paleo-Indian occupations found near other springs in the Edwards Plateau area, may have been semi-sedentary in their settlement activities. This hypothesis has been strongly contested by Johnson and Holliday (1984).

It should be noted here, as an aside, that numerous occurrences of elephant remains and other Pleistocene fauna have been found below the Balcones Escarpment. These include finds near Fort Inge in Uvalde County, on the Cain Ranch in Zavala County, in gravel-mining operations in northern Bexar County and on Congress Avenue in Austin. Most of the elephant species represented have not been identified or dated; no associated artifacts have been found.

Although west of the escarpment, in Val Verde County, site 41VV162A near the Rio Grande, contains loose, ashy deposits in which late Pleistocene fauna were found. Most of the bones were burned and broken. The lowest of three zones discerned in the deposits contained flakes, a uniface, and the cut bone of a small, extinct antelope (cf. Capromeryx). Two radiocarbon assays, on charcoal, place the age of this lower zone at 13,200-14,300 B.P. In the overlying, intermediate zone, several more flakes, a Clear Fork tool, and many burned and broken animal bones were discovered; a radiocarbon date of 12,280 B.P. was obtained. This highly important site has not yet been fully published, but a brief description can be found in Collins (1976).

Also in Val Verde County is Bonfire Shelter (Dibble and Lorrain 1968; Bement 1986), one of the most significant Paleo-Indian sites in the state. It contains several bone bed deposits, with the most recent, Bone Bed 3, dated at ca. 2500 years ago and containing the remains of modern bison (Bison bison). However, Bone Bed 2 dates to ca. 10,230 years ago, and represents bison jump episodes in Paleo-Indian times. Folsom and Plainview points are found in this bone bed, associated with the remains of extinct bison (Bison antiquus or occidentalis). As many as eight Late Pleistocene bone deposits underlie Bone Bed 2, as first recognized by Dibble and Lorrain (1968) and recently studied by Bement (1986). It is not clear whether the fauna in these deposits represent human procurement activities (jumps or use of the shelter as an animal trap) or those of carnivores. A Rancholabrean faunal assemblage comes from these deposits, containing the remains of elephant (Mammuthus sp.), bison, camel (Camelops hesternus), horse (Equus francisci), and small antelope (Capromeryx sp.); in addition, the gray fox (Urocyon cinereoargenteus), which still lives in the area today, is also represented. A radiocarbon date of 12,460 ± 490 was obtained from charcoal flecks found in one of the bone concentrations, with a horse-camel-mammoth association.

Late Paleo-Indian Sites

Sites of Late Paleo-Indian times, with non-fluted lanceolate points, have been reported from many parts of the Balcones Escarpment. Many of these are surface assemblages, although some, like the Gamenthaler Creek site (in Gillespie County; Thomas C. Kelly, pers. comm., 1985), likely have buried components. Vance T. Holliday (University of Wisconsin) is currently preparing a geomorphological analysis of the Gamenthaler deposits and his research may point the way to the study of other possible buried sites in the area.

The Wilson-Leonard site (41WM235) in Williamson County, excavated by the State Department of Highways and Public Transportation, is undoubtedly the most significant Paleo-Indian site excavated in the region. While there are no fluted points, the basal part of the deposits may well date into the Early Paleo-Indian era. However, regional archaeologists expect the Late Paleo-Indian deposits at Wilson-Leonard to provide new data on chronological sequence, absolute dating, and associated tool sets. This open campsite has been reported in very preliminary fashion by Weir (1985). Below stratified Archaic occupations, Weir reports a sequence of Angostura, Scottsbluff, and Plainview habitations, with the "Wilson" component (with expanding stem and lanceolate points) at the bottom. Of special note was the discovery of a well-preserved semiflexed female burial dating to the early part of the Wilson-Leonard Paleo-Indian sequence. A tandem accelerator date of 1 mg of charcoal from the burial pit yielded a radiocarbon assay of 13,000 ± 3000 years (Weir 1985); two other carbon-14 dates from soil humates are 9470 ± 170 and 9650 ± 120 years B.P. Weir believes the latter dates to be most applicable to the burial.

A small, in situ occupation of Plainview age (ca. 8200 B.C.) has been excavated at the St. Mary's Hall site, along Salado Creek in northern Bexar County. Two preliminary reports have been published (Hester, 1978, 1979) and work on a final manuscript is underway. The site is located on a colluvial downslope overlooking Salado Creek, a major tributary of the San Antonio River. The site is situated atop one of the highest points in the Salado valley, at an elevation of approximately 760 feet above sea level, about 35 meters west of the present stream channel.

In this paper, only the materials from area A are discussed. It was within this area that a Plainview occupation was found. The typical stratigraphy is as follows: the upper unit is a brownish-gray midden with scattered burned rock, hearths, and one extensive accumulation of large burned rock. This stratum extends to a depth of 40-50 cm, and contains Late Prehistoric artifacts in the upper part, with Late Archaic (and occasional Middle Archaic) materials in the lower portion. At 60-75 cm, there is a stratigraphic unit composed of brownish soil and caliche gravels and within this stratum Early Archaic artifacts were found. Below this is a stratum referred to as the "gravels," composed of caliche nodules or gravels with interstices of weathered limestone clasts. Geomorphologists Dr. Charles M. Woodruff and Glen L. Evans (pers. comm., 1977) describe the unit as having been formed by colluvial slopewash. On top of the gravel unit, Late Paleo-Indian specimens such as Golondrina and Angostura were found, with Golondrina at a lower stratigraphic position.

Part of the gravel unit has been badly disturbed by the formation of caliche "balls" or conglomerates. The mechanisms which caused the formation of these very disruptive features are poorly known. Woodruff offered two possible explanations: (1) they are a local soil phenomenon caused by underground water flow or percolation; or (2) a local ephemeral stream once coursed through a portion of the site leaving limey deposits. The possibility of an erosional or streamlike area is supported by our excavations. Fortunately, a large part of area A had been spared the presence of caliche "balls," and this was where we concentrated our excavation efforts.

In the gravel units, an occupation tentatively identified as the Plainview period was found about 15-20 cm into the stratum. Cultural materials were extensive and were precisely documented. This occupation will be focused on below.

The occupation is considered in situ by our geological consultants and is sealed within the gravel unit. Except on the northern margins, where the caliche conglomerates occur, it is undisturbed. The best measurements available at this time indicate that the area utilized by the Plainview peoples is 8 meters long, north to south and about 6 meters wide (48 m^2 or about 157 square feet). Diagnostic projectile points were clustered near the central part of this area (Fig. 5). Several hundred pieces of chert chipping debris were scattered throughout the occupation area.

Other stone tool forms include trimmed or edge-modified flakes, steep bitted unifaces in the form of end scrapers, a large bifacial Clear Fork tool, a heavily worn chopper, thinned bifaces perhaps used as knives, numerous preforms (representing unfinished points) and a number of cores (Fig. 5). The set of points, trimmed flakes, formal unifacial and bifacial tools, some scattered animal bones (deer and bison-sized) and burned hearthstones are indicative of campsite activities. The numerous preforms and cores, and the substantial amount of debitage, suggest lithic workshop activities associated with the campsite. That is, there was considerable emphasis on chert-working, over and above that necessary for maintenance purposes.

The caliche gravels in which the materials are buried do not, apparently, indicate any particular climatic and environmental situation. Both Woodruff and Evans believe the "calichefication" is a normal soil process in the site area; Evans believes that the occupation was probably originally buried in clay-loam soils of the type that constitute the uppermost soil horizon in the valley today.

Two Val Verde County sites have also yielded distinctive Late Paleo-Indian materials. The Devil's Mouth site (Johnson 1964) is a deeply buried terrace site. In area C of the site, a number of Paleo-Indian projectile points were found, and a radiocarbon date of ca. 8700 B.P. was obtained (Sorrow 1968). This date is related to the Golondrina Complex, a Late Paleo-Indian cultural pattern that was later also recognized at Baker Cave (Word and Douglas 1970). At that site, the Golondrina materials were stratified near the base of a deep rockshelter deposit and dated by several radiocarbon assays at ca. 9000 B.P. A hearth excavated in the Golondrina stratum in 1976 (Chadderdon 1983; Hester 1983) contained an abundance of plant and animal remains. All of these materials are clearly post-Pleistocene. The absence of certain desert plant species from this hearth and elsewhere in the Golondrina occupation suggests that the area was somewhat more moist than in modern times. The array of faunal species included small mammals and rodents, reptiles, and fish; most intriguing is the presence of bones from 16 different snake species, many of them charred from cooking (Hester 1980, 1983).

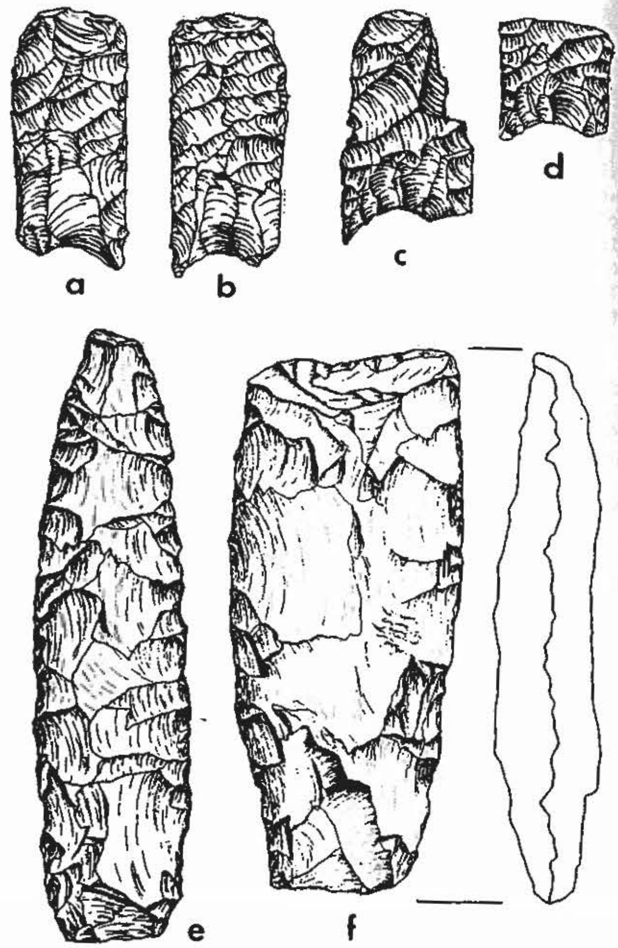

Figure 5. Artifacts from the Plainview Occupation at St. Mary's Hall Site. a,b, both sides of Plainview point; c,d, Plainview point basal fragments; e, preform (unfinished Plainview point), f, bifacial Clear Fork tool (cross-section is shown). Length of e, 107 mm. Drawings of a-d by Margaret Greco; e,f, were drawn by Dennis Knepper.

The Golondrina Complex, characterized by the distinctive Golondrina projectile point type (Fig. 2), is a widespread pattern at ca. 9000 B.P. It extends from central Texas and along the Balcones Escarpment into southern Texas and Nuevo Leon, Mexico (the San Isidro site; Epstein 1969).

CONCLUDING REMARKS

In this paper, it has been possible to briefly review the prehistoric cultural chronology of the Balcones Escarpment area, focusing on those sites attributable to late Pleistocene-early Holocene times. It is obvious that many problems exist, especially when looking at the early sites. There are few excavated components and some of the potentially most significant sites have not yet been published. There are a paucity of radiocarbon dates and only vague temporal parameters can be drawn at present. The earliest diagnostic remains are recognized in the form of Clovis and Folsom fluted points found at occupation sites in the region. Other distinctive diagnostics, such as Plainview and Golondrina points, represent Paleo-Indian activities between 8200-7000 B.C. The close of the Paleo-Indian period can be but dimly discerned. The Scottsbluff point type, dated on the Plains at ca. 6500 B.C., is found in stratified contexts only at the Wilson-Leonard site in Travis County (Weir, 1985, p. 3). Interestingly, the Angostura point type--subject of considerable typological debate among Texas archaeologists--is stratified just above Scottsbluff, and just below Early Archaic occupations, at Wilson-Leonard. Though few pertinent radiocarbon dates are yet available, it is likely that Angostura dates in the general 6000 B.C. time frame (Hester and others, 1985).

However, chronology is only one problem in regional Paleo-Indian research. More important issues dealing with subsistence, technology, and settlement remain to be addressed. Again, the Wilson-Leonard data will doubtless provide new insights, but they will represent a single site and we need information from a broad spectrum of sites to delimit meaningful patterns. Despite all of the intensive research of recent years, new Paleo-Indian sites are still found only occasionally. Part of the problem is that archaeologists do not know where to look for such sites or how to evaluate the potential of these sites when buried materials are found. The help of geologists, especially in the area of geomorphology, is badly needed. Presently there are but a few trained specialists of this sort who have interests that relate to archaeological deposits. Geomorphological research is needed not just for the Paleo-Indian era, but for interdisciplinary studies at prehistoric sites throughout the time range. For example, studies of alluvial gravel deposits may be instructive in terms of ancient climatic trends. Additionally, in some situations, even Archaic sites are deeply buried and would be missed by standard archaeological surveys. A case in point is in the area of the proposed Applewhite Reservoir along the Medina River in Bexar County. Archaic sites are so deeply buried in terrace deposits that their presence can be noted only in deep gully exposures. Or, in situations where it was predicted that such sites might be found, only deep testing with a backhoe brought them to light. Clearly, major research projects need the involvement and advice of geomorphologists if the quality of archaeology in the Balcones Escarpment area is to improve.

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THE PLEISTOCENE TERRA ROSSA OF CENTRAL TEXAS

Keith Young
Department of Geological Sciences
The University of Texas at Austin
Austin, TX 78713

ABSTRACT

Scattered over Central Texas at a number of localities are remnants of a terra rossa (paleosol). Usually the A-horizon and upper part of the B-horizon have been removed by erosion. But the B-horizon, especially its lower part, can be seen in many areas. As is typical of terras rossas, the base of the profile seldom has a C-horizon, is usually diagenetically altered, and is often truncated. The age of formation of the Central Texas Terra Rossa is between 0.73 and 2.0 m.y. B.P.

INTRODUCTION

Relict to parts of Central Texas is a terra rossa. Perusing the literature, I was surprised to discover how seldom it is mentioned, even in theses that were mapped in areas with terra rossa. The purpose of this paper is to increase interest in this terra rossa by discussing its distribution, geology, and age. Only incomplete conclusions can be drawn because of insufficient study.

TERRAS ROSSAS

The concepts of terra rossa (from the Italian term "terra rossa" terre rosse, pl.; sometimes misspelled "terra rosa") have varied considerably over the years since the first discussion of the subject by Fuchs in 1875, some 26 years after the term was introduced in the Italian literature (Joffe, 1949). Terras rossas in parts of the United States have recently been discussed by Ruhe (1975), Hall (1976), and Quinlan (1978), but before this the attitude of American pedologists had generally been one of ignoring the term, because in their opinion the term was used inconsistently (Baldwin et al., 1938). But if that were a good reason, we would not be able to use any early names in many fields.

Terras rossas were first named and described in Italy (Joffe, 1949). The present Mediterranean climate is xerophytic in many areas where there are now terras rossas, and even the rendzinas in Serbia occur in a climate with only 800 to 900 mm of rainfall per year (Tanasijević et al., 1966). This is true also of terras rossas (sometimes called rendzinas) of Spain.

Joffe (1949) suggested that the true terras rossas developed on limestone are paleosols formed under a more humid climate, usually considered to have had 1500 mm or more of rainfall per year, although even this is not a consistent figure among various authors. Whether Joffe's usage is the first suggestion of paleosols for these terras rossas I do not know, but Joffe (1949) gives credit for the idea to no one before him, and his historical summary, though short, is fairly good. Shaw (1974) refers to the Central Texas Terra Rossa as "residual terra rosa," and Quinlan (1978) refers to the mid-continent (United States) terras rossas as paleosols, even though they are interpreted to have had fluvial products added to the residual insolubles of the limestone.

Duchanfour (1970) uses the term terra rossa only for paleosols formed on limestone terrains under a climate of greater rainfall and higher temperature than the present Mediterranean climate. Much past confusion in America seems to have resulted from trying to produce these soils within the present climatic regime of a particular area. Duchanfour (1970) lists several characters of terras rossas:

1) A_1- and A_2B-horizons are frequently removed by erosion.
2) The B-horizon is very argillaceous, as is the A_2B-horizon, and passes into a BC-horizon with pockets of clay and corroded limestone.
3) A C-horizon is sporadically present in deeper fissures.
4) Siliceous (quartzose) constituents are common.
5) Pulverulitic limestone is common.
6) At depth the soil was constantly humid during all seasons.
7) At some localities the dominant clay is kaolinite; at others it is illite.
8) In forested areas the color may be more brownish.
9) Frequently the soils are truncated at the base.

Duchanfour (1970) emphasizes that these terras rossas date from a former, Pleistocene interglacial, are therefore paleosols, and have undergone a large amount of diagenesis, especially in the horizons below the upper part of the B-horizon. That the soils Duchanfour (1970) and most other European pedologists now refer to as terras rossas are largely eolian is refuted by their occurrence only on limestone terrains. If the soils are browner, a forested canopy may be indicated at the time of their formation.

Under these definitions, avoiding arguments of in situ or eolian origins, terras rossas are diagenetically altered paleosols that formed on limestone terrains under humid and tropical or nearly tropical, climatic regimes of approximately 1500 mm or more of rainfall per year.

DISTRIBUTION OF THE CENTRAL TEXAS TERRA ROSSA

The areal extent of the Central Texas Terra Rossa is incompletely known because the boundaries have never been mapped. Figure 1 shows four areas in Central Texas within which terra rossa can be viewed, but the boundaries of these areas are approximate, and there are smaller, internal areas from

in Abbott, Patrick L. and Woodruff, C.M., Jr., eds., 1986, **The Balcones Escarpment, Central Texas:** Geological Society of America, p. 63-70

which the terra rossa has been removed. Much of the high, karstic plain of Woodruff and Abbott (1979, fig. 6) is covered with terra rossa, but terra rossa extends beyond some of the areas they have denoted and has subsequently been removed from other areas.

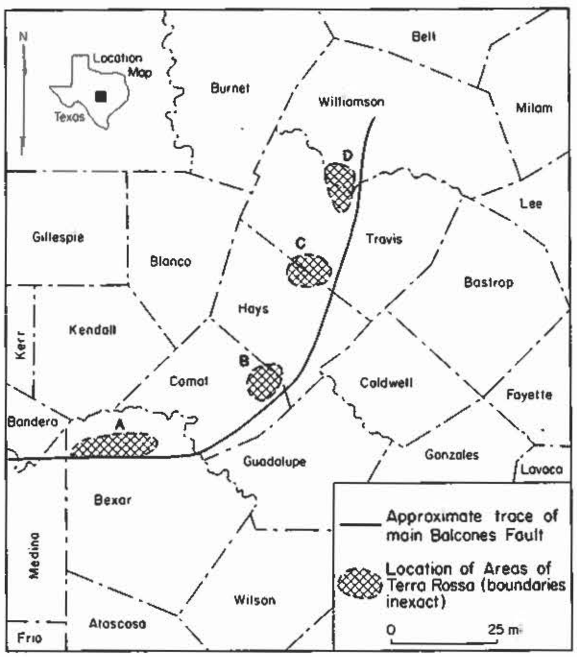


Figure 1. Four areas containing major outcrops of Central Texas Terra Rossa. Terra rossa is not continuous since it has been completely removed by erosion in some areas. Silicified fossils and remnants of red clay indicate that terra rossa was once very widespread.

Associated with much of the Central Texas Terra Rossa is extensive, Pleistocene silicification of Cretaceous fossils. Some other areas, not within the localities of Figure 1, yielding silicified Cretaceous fossils (Ikins and Clabaugh, 1940; Stanton, 1947; Moore, 1964) may represent Pleistocene silicification, with other evidence for terra rossa either less obvious or unrecorded. On the divide between Kerrville and Fredericksburg along State Highway 16, there is terra rossa. This terra rossa seems to be associated with the collapse of the Kirschberg Gypsum described by Barnes (1946); it may be Pleistocene. Other terras rossas, such as that on the Ellenberger Limestone just a few miles southeast of Brady on the divide between Brady Creek and the San Saba River, are probably Paleozoic. Studies of all of these terras rossas would lead to a greater understanding of the geology of Central Texas.

SOIL PROFILE

The soil profile for a terra rossa is not easily defined. This apparently accounts for terms such as "BC-horizon" in Duchanfour (1970). Figure 2 represents a profile from the Central Texas Terra Rossa along Loop 1604 north of San Antonio, 1.4 miles east of its intersection with U.S. Highway 287. The profile is developed on Person Formation, the upper formation of the Edwards Group (Rose, 1972), and it is not truncated at the base as are some profiles. A truncated soil is a soil in which the red clay of the B-horizon rests directly on unaltered limestone. Frequently the larger karren are not developed on bare rock, but on the limestone beneath the B-horizon. With such a truncated soil it is generally assumed that there has been some movement of soil into or onto these areas (Duchanfour, 1979), and that the base of the profile is not a natural product of mechanical or chemical weathering.

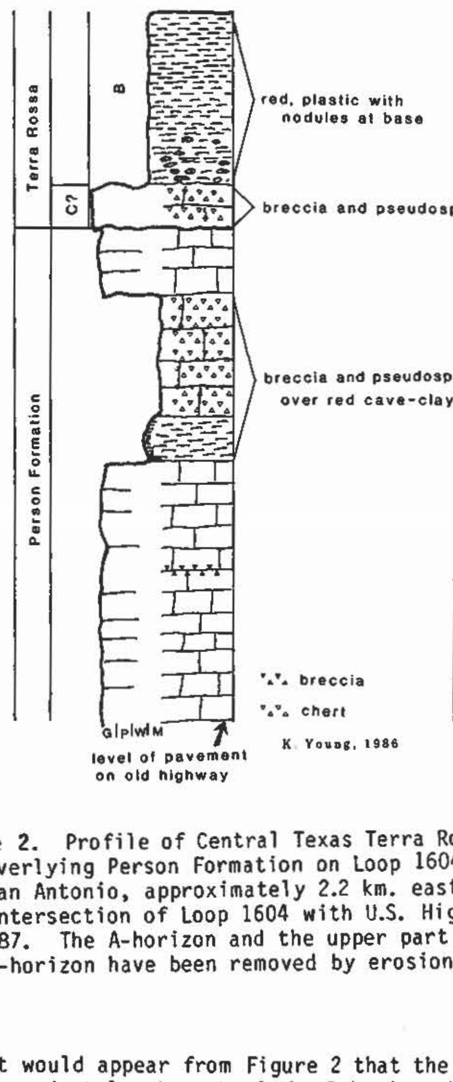


Figure 2. Profile of Central Texas Terra Rossa overlying Person Formation on Loop 1604, north San Antonio, approximately 2.2 km. east of the intersection of Loop 1604 with U.S. Highway 287. The A-horizon and the upper part of the B-horizon have been removed by erosion.

It would appear from Figure 2 that the A-horizon and at least part of the B-horizon have been removed by erosion. Most of the B-horizon is red, somewhat plastic clay. The lower part of the horizon is apparently B_2, with limestone and caliche nodules; the latter could, of course, be post-terra rossa. If there is a C-horizon, it is now represented by a cave-fill-like breccia composed largely of pseudosparite at the base of the profile. This pseudosparite is almost identical to the pseudosparite, which is cave-fill associated with redeposited, red clay, within the underlying Person Formation. According to Duchanfour (1970) such diagenetic alterations are typical of the basal parts of profiles of terras rossas.

At other localities the Central Texas Terra Rossa can be seen to be truncated, and on the Kainer Formation there may be well-developed C-horizon.

GEOLOGY

It is generally stated that a minimum of 1500 mm of rainfall per year is necessary to produce terra rossa. In addition to the minimum rainfall, Mediterranean terras rossas also required yearly dry-wet cycles, but not sufficiently dry to remove moisture from horizons below the upper part of the B-horizon (Duchanfour, 1970). I have seen no horizon of plinthite in the Central Texas Terra Rossa to indicate a marked seasonal change in the level of the water table. The above requirements already place certain restrictions on the age of the Central Texas Terra Rossa, because 1500 mm or more of rainfall is not normal to Central Texas.

Surficial Geology

The Central Texas Terra Rossa is sufficiently ancient in the Pleistocene that it has been dissected, sometimes removed completely, and diagenetically altered.

In addition to the Central Texas Terra Rossa shown in Figure 1, other areas once covered by it, but not shown, may be indicated by accumulations of red clay in caves and shallow subsurface or by the occurrence of extensive silicification of Cretaceous fossils. The area mapped as high karstic plain by Woodruff and Abbott (1979) in the Cibolo Creek drainage was probably covered with terra rossa at one time, since the caves and collapse zones in the Person Formation contain much red clay and red-stained rock and pseudosparite (Newcomb, 1971). Some of this area has not been studied closely, and there may still remain outcrops of terra rossa.

Between Purgatory Creek and the Guadalupe River along much of Purgatory Road (locality B of Figure 1), the Central Texas Terra Rossa is associated with a pediment cutting across Kainer, Person, Georgetown, Del Rio, Buda, and Dessau formations. Much of this area is the high, karstic plain of Woodruff and Abbott (1979). The Kainer and Person formations and the Buda and Dessau formations are in fault contact. At some localities along this pediment the terra rossa has been removed. Along the Freeman Ranch-Bear Creek fault zone and along the Bat Cave fault there are rows of dolines (Figures 3 and 4) (Noyes and Young, 1960). These faults have the reverse drag on the down-thrown block (Bills, 1957; Tucker, 1968), which allowed water to flow laterally along the faults toward Purgatory Springs instead of down the regional dip. This further resulted in a series of dolines, probably collapse dolines, along the faults. One of these dolines, illustrated in Figure 4, is on the old Wegner Ranch on the northeast side of Purgatory Road.

The silicified, fossil trees described as coming from an unconformity between the Edwards and Georgetown Formations by Cronin (1932) are actually Pleistocene. They come from the red clay that accumulated in the dolines along Purgatory Road, including the doline pictured in Figure 4. Such fossil wood should not be confused with Cretaceous wood found around the Devils River Trend.

Along Loop 1604, in San Antonio (locality A, Figure 1), the Central Texas Terra Rossa occupies an area that is nearly flat but dissected locally. The streams in this area with rejuvenated meanders (Shaw, 1974) may have originated on this surface.

Although there is no visible terra rossa on the Welch Ranch (now southwest Round Rock, Williamson County), terra rossa occurs just southwest of the area (locality D, Figure 1). On the Welch Ranch, grainstone at the top of the Edwards Limestone contained several cenotes that had been fenced so that cattle could not fall in and drown. One cenote was full of water to within one meter of the surface of the ground in 1965 when I mapped the area.

That lithology was important in the development of the Central Texas Terra Rossa is suggested by its rarity on the Glen Rose Formation and its dominance on rocks on the Edwards Group. Even within the limestones of the Edwards Group, karstification of the Person Formation is much more thorough than karstification of the Kainer Formation, even though the Central Texas Terra Rossa extends uninterruptedly across their contacts (usually fault contacts). Terra rossa has not been observed on the formations of the Austin Group, but outcrops of Dessau Formation on the edge of the Edwards Plateau are so small and uncommon (Young, 1985, 1986) that this may have no meaning.

Silica, usually microquartz, is commonly associated with the Central Texas Terra Rossa as with other terras rossas (Duchanfour, 1970). Along Purgatory Road at localities where the terra rossa has largely been removed, the surface of the pediment is commonly strewn with fragments (mostly from 5 to 30 cm in size) of silicified rudists, largely of specimens of the genera Caprinuloidea and Texicaprina.

The section of Person Formation (Figure 5) along Loop 433 South, New Braunfels, Comal County, contains about 50 percent pseudosparite and associated, red cave-clay and cave-breccia. Other beds show that at least some of the rock was originally cross-bedded, coarse grainstone.

Although no terra rossa is on the surface, red cave-fill in Inner Space Caverns (Woodruff et al., 1985) near Georgetown, Williamson County, indicates a source of red clay (terra rossa) not too distant.

Subsurficial Geology

In this section only the shallow subsurface is considered--sufficiently shallow that there could be evidence of an overlying terra rossa or of a former terra rossa. In 1969 a coring program was carried out for a proposed quarry along Alligator (Geronimo) Creek just above the Balcones scarp, south of Hunter, Hays County. (Samples of the cores are in the collections of the Texas Memorial Museum, University of Texas at Austin.) Cores verified some of the previously mentioned surficial observations, because the Person Formation was much more highly altered, diagenetically, than was the Kainer Formation. These cores also demonstrated three intervals of formation of cave-fill. Of course there were more than three, but they cannot all be demonstrated readily. In these cores it was possible to see (1) an older, unstained cave-fill, which was cut by (2) an iron-stained (red) cave-fill related to the Central Texas Terra Rossa, which in turn was cut by (3) a younger, unstained cave-fill, deposited after the period of formation of the

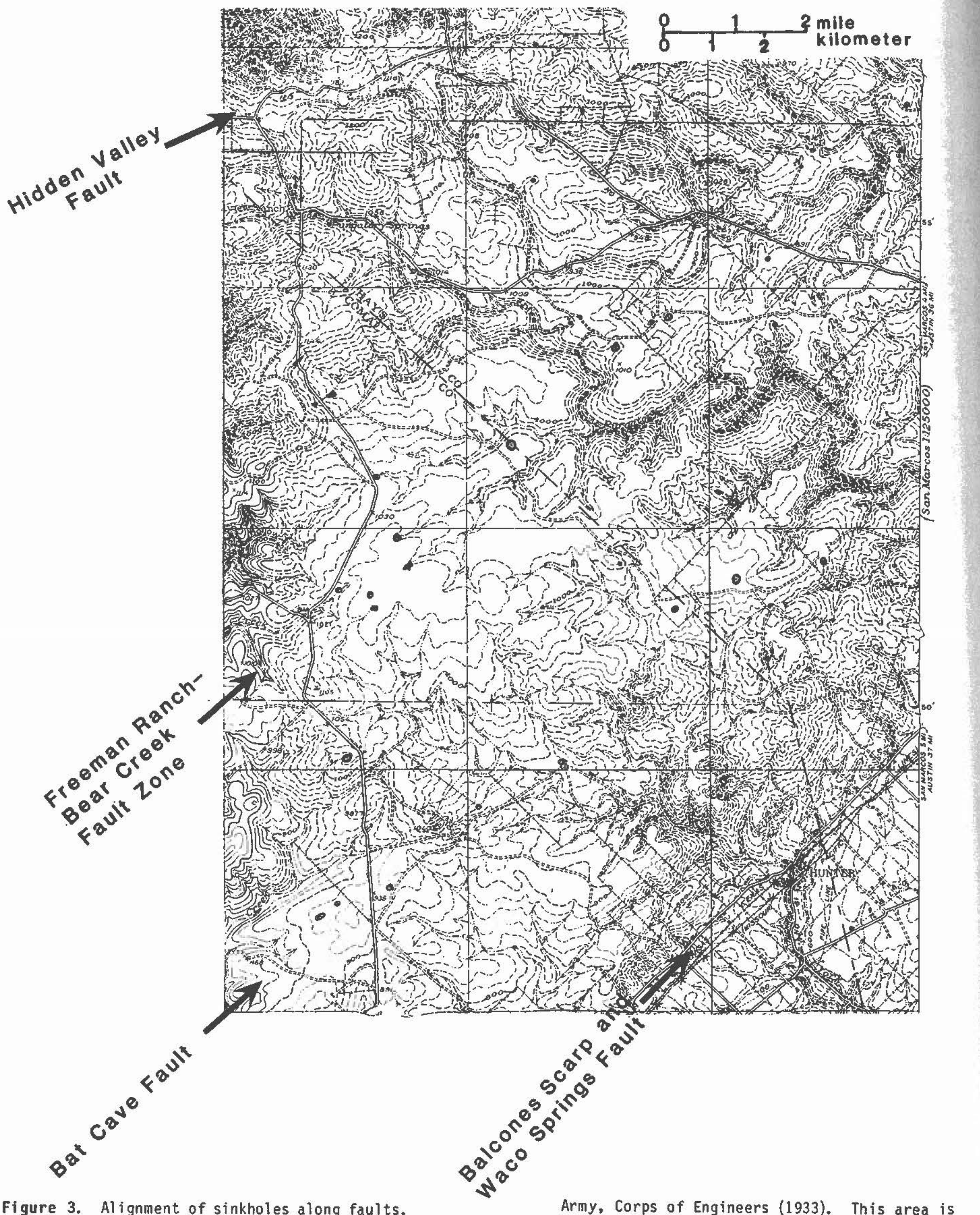


Figure 3. Alignment of sinkholes along faults. Many of these sinkholes have been plugged with red clay from the terra rossa and are full of water at least during wet weather. This figure is somewhat reduced from that of the U. S. Army, Corps of Engineers (1933). This area is part of the high karstic plain of Woodruff and Abbott (1979) and lies between the Blanco River and the Guadalupe River.

Figure 4. Doline on the old Wegner Ranch. This is one of the sinkholes along the Freeman Ranch-Bear Creek Fault Zone just off Purgatory Road, Comal County, Texas.

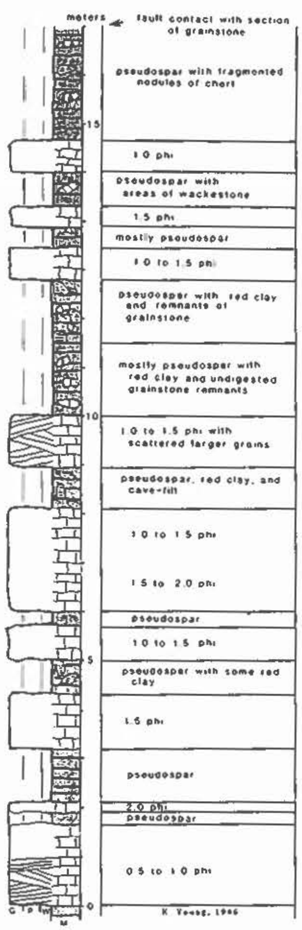


Figure 5. Section of Person Formation along Loop 433 South, New Braunfels, Comal County, Texas. The rock is approximately 50 percent cave-deposits.

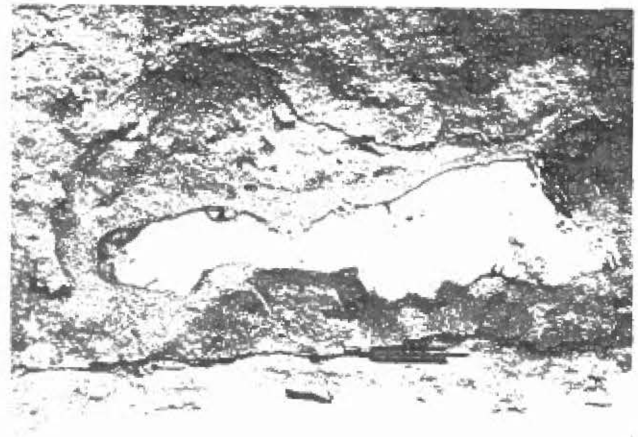
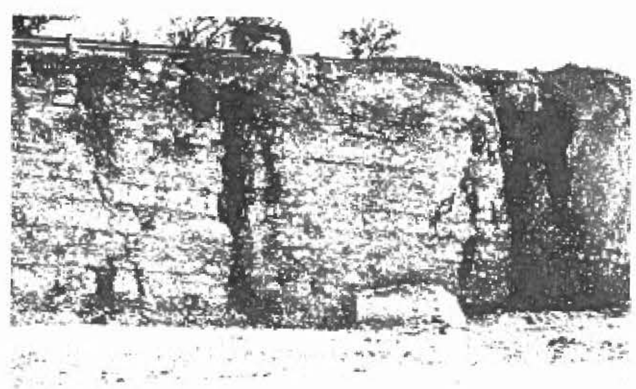


Figure 6. Etched and embayed chert nodule from the Fort Terrett Formation, about 20 feet below the collapse zone of the Kirschberg Gypsum, 2.0 to 2.5 km. southeast of Junction, Kimble County, Texas, on Interstate 10.



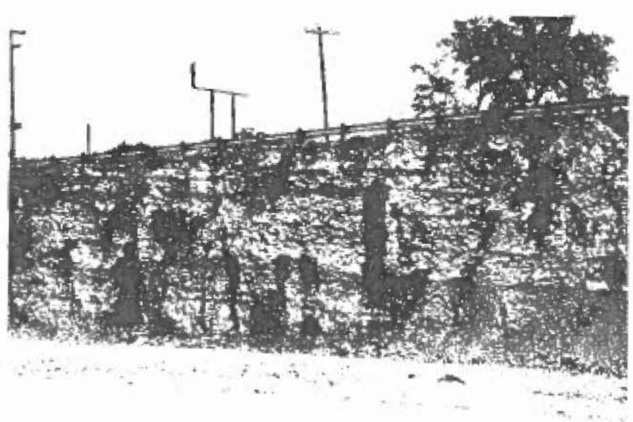


Figure 7. Two views of geologic organs (solution cavities and widened fractures filled with red clay derived from overlying terra rossa) in the Person Formation, north San Antonio, along Loope 1604 just east of its intersection with Interstate 10, Bexar County, Texas.

Central Texas Terra Rossa. However, the ages are relative because, at present in areas of terra rossa, cave-fill that is being deposited may be red, whereas in areas of no terra rossa the cave-fill is unstained.

During coring the bit would frequently drop the full length of the kelly, and the travelling block would bounce on the rotary table. Most often, however, the caverns had been collapsed, and the recovered core would pass from limestone into red cave-clay, clay-breccia, or pseudosparite.

According to Duchanfour (1970) there has been some diagenesis of all terras rossas. The diagenesis of the Central Texas Terra Rossa has not been studied, but one can assume that it is generally one or more of the types attributed by Ellis (1985) to meteoric water. Certainly the superficial appearance of what may be the C-horizon (Figure 2) is similar to the pseudosparite that represents ancient cave-fill (probably derived from the terra rossa) in the underlying Person Formation.

That silica (usually microquartz) is a common constituent of terras rossas (Duchanfour, 1970) does not mean that all silicification of the Cretaceous fossils occurred during the formation of the Central Texas Terra Rossa, but the many occurrences of silicified fossils in red cave-clay and in the profile of the terra rossa itself suggest high mobility of silica at the time of formation of the terra rossa.

In the highway cuts on Interstate Highway 10 in the hills southeast of Junction, Kimble County, there is exposed a collapsed zone where the Kirschberg Gypsum has been removed by solution. Removal of the gypsum would have been most active during the period of higher rainfall represented by formation of the terra rossa. At this particular locality, for depths up to 10 meters below the base of the Kirschberg level, the undersides of the chert nodules have been deeply etched and embayed (Figure 6). This embayment presumably occurred with the abnormal salinities produced by solution of the gypsum by meteoric water. Certainly at this time silica seems to have been mobilized and redeposited by the silicification of fossils.

Many fractures, widened by solution (Figure 7), and other geologic organs appear to be associated with, or were just subsequent to, the formation of the Central Texas Terra Rossa.

ATTEMPTS TO DATE THE CENTRAL TEXAS TERRA ROSSA

Dating the Central Texas Terra Rossa has not been easy. Approaches can be made from the following disciplines: (1) geomorphology, (2) paleoclimatology, (3) diagenesis, (4) redeposition, (5) paleontology, and (6) paleomagnetism.

Geomorphology

The relation of outcropping areas of Central Texas Terra Rossa to earlier Pleistocene channels of the Guadalupe and Blanco Rivers (Koenig, 1940; Woodruff, 1977) indicates that this terra rossa formed prior to the capture of these streams. These captures may also correlate chronologically with primary drainage change on the Brazos River as described by Stricklin (1961) and Hibbard and Dahlquest (1967). Hibbard and Taylor (1960) consider major changes of drainage in Kansas and adjacent Oklahoma to be at the end of the depositi of the "Yarmouthian" (Crooked Creek Formation of Kansas = Seymour Formation of North Texas).

Since "Yarmouthian" and "Illinoisian" do not mean the same to everyone, I should point out that am using the terms as I read them in Hibbard (1970 Hibbard and Dahlquest (1967), and Hibbard and Taylc (1960). Hibbard and Dahlquest (1967) suggested tha the climate of North Texas in the Late "Yarmouthiar was subhumid, mesothermal, frost-free, and maritime Later, Hibbard (1970) dated most of the drainage changes of the Great Plains, including those of North Texas, as occurring with a change of climate from subhumid to much drier at or near the end of the "Yarmouthian."

If the tectonics or climatic changes that altered the courses of the streams and resulted in rejuvenation were as regional as they seem to be, one would suspect that the streams of south-central Texas changed at the same time--that is, during the Late "Yarmouthian" of Hibbard (1970).

Paleoclimatology

The climatic requirements of greater humidity and particularly of greater rainfall for a terra rossa do not tell us much about age, other than that the Central Texas Terra Rossa is not recent. However, the required greater rainfall (at least more than twice the present rainfall average of 700 mm per year at San Antonio) tells us that all of the Central Texas Terra Rossa was formed at the same time, because a consistent, long-term, high rainfall at different times in different local areas would be impossible. Furthermore, glacial stages would be excluded because of low temperature and probably insufficient rainfall. These data agree with those for the rejuvenation and change in stream courses mentioned above.

Diagenesis

Duchanfour (1970) considers the amount of diagenesis of terras rossas of the Mediterranean region too great to have been completed in the Recent Interglacial.

Redeposition

At some localities red clay, reworked from the Central Texas Terra Rossa, has been deposited before modern drainage developed. There is a deposit of reworked red clay on Waller Creek, just below 51st Street in Austin, Travis County, that was transported across the present area of drainage of Shoal Creek prior to the development of this drainage area. Also redeposition in caves occurred both during and after the formation of the Central Texas Terra Rossa.

From all of this evidence, then, the Central Texas Terra Rossa was formed between the Kansan and the Holocene. Glacial stages would be excluded because of climatic restrictions.

AGE OF THE CENTRAL TEXAS TERRA ROSSA

Recently, both paleontologic and geomagnetic data have greatly reduced the margin of error in dating the Central Texas Terra Rossa. From a small cave filled with red clay derived from the terra rossa in the Murchison Quarry (Fyllan Cave Local

Fauna), northwest Austin, Texas, Taylor (1982, 1986) has described a Middle Irvingtonian fauna. This fauna is Late "Yarmouthian" and pre-"Illinoisian."

Furthermore, during deposition of the red clay in the cave there was a magnetic-reversal anomaly, since some samples are reversed and some are not. The reversal from Matuyama to Brunhes is known to have occurred in Late Middle Irvingtonian (Taylor, 1982). Also, the Jaramillo event just preceded the Matuyama-Brunhes reversal. If this anomaly represents reversal from Matuyama to Brunhes, then the fauna is about 0.73 m.y. B.P. (Taylor, 1986).

The paleo-ecological analysis of Taylor (1982) would indicate that the cave-fill for the Fyllam Cave Local Fauna was deposited after the formation of the Central Texas Terra Rossa, because the fauna seems to represent an environment of less humidity and rainfall than is required for the development of terra rossa. Both the paleomagnetic and paleoecologic data of Taylor (1982, 1986) agree with geomorphologic, climatic, and paleoecologic conclusions of Hibbard and Taylor (1960), Stricklin (1961), Hibbard and Dahlequest (1967), and Hibbard (1970).

Thus the age of the Central Texas Terra Rossa would appear to be older than Middle Irvingtonian (0.73 m.y. B.P.) and younger than "Kansan," probably Early and/or Middle "Yarmouthian."

SUMMARY

The Central Texas Terra Rossa is a widespread paleosol with all the implications ascribed to terras rossas by Duchanfour (1970). It was widespread before partial removal. It represents a time of higher humidity and greater rainfall (1500 mm or more per year) than occurs in Central Texas at present (about 700 mm per year). The best dates for the formation of the Central Texas Terra Rossa are Early and/or Middle "Yarmouthian," that is, between 0.73 m.y. and 2.0 m.y. B.P., prior to the Brunhes Normal and the regional climatic change at the end of or within the Late "Yarmouthian."

ACKNOWLEDGEMENTS

I first became aware of the Central Texas Terra Rossa in the sping of 1949, while visiting outcrops northeast of Wimberly with F. L. Whitney. The Geology Foundation and the Research Institute, both at the University of Texas at Austin, have supported a number of projects in this area, and, therefore, have unknowingly supported this project. Geologic mapping for the Bureau of Economic Geology on other projects also aided this presentation, and Patrick L. Abbott and C. M. Woodruff, Jr., encouraged me.

Jeff Horowitz prepared Figure 1, and Rosemary Brant prepared the camera-ready copy.

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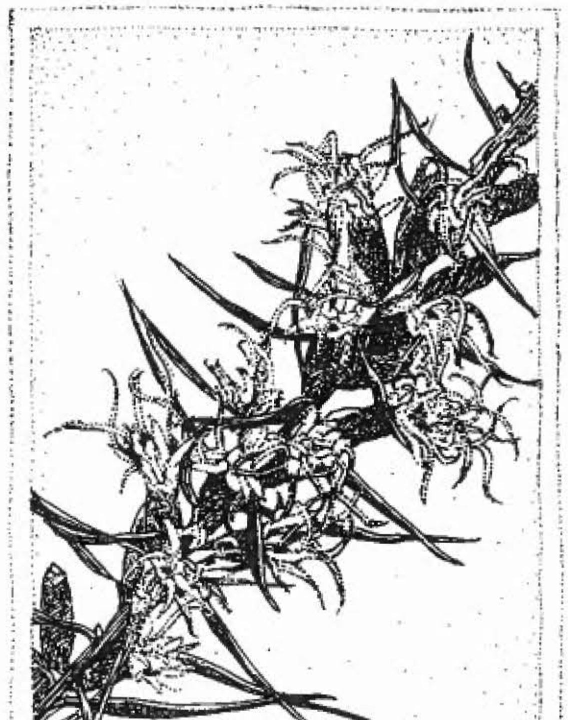

LIATRIS MUCRONATA . M Campbell
GAY FEATHER

STRUCTURAL STYLE IN AN EN ECHELON FAULT SYSTEM, BALCONES FAULT ZONE, CENTRAL TEXAS: GEOMORPHOLOGIC AND HYDROLOGIC IMPLICATIONS

Thomas W. Grimshaw
Radian Corporation
P. O. Box 9948
Austin, Texas 78766

C. M. Woodruff, Jr.
Consulting Geologist
P. O. Box 13252
Austin, Texas 78711

ABSTRACT

Detailed geologic mapping in the Balcones fault zone in the San Marcos area has revealed a structural style that may have had a profound effect on the geomorphologic and hydrologic evolution of the area. Two major en echelon step fault zones are present in the area, and a highly faulted ramp structure has formed in the zone between the en echelon fault zones.

Differential erosion of rock units in the ramp structure may have determined the course of a stream which captured the Blanco River from an easterly flow direction into the Onion Creek basin to its current southeasterly flow direction. Subsequently, the Blanco may have "tapped" the Edwards aquifer by down-cutting or side-cutting action at or near the San Marcos Springs location. Thus, both the capture of the Blanco and the current location of San Marcos Springs hay have been indirectly caused by the local structural setting between the two major en echelon fault zones of the Balcones system.

Similar major ramp structures are apparent by map inspection in at least three other locations in the Balcones fault zone, one near Austin and two west of San Antonio. A fourth structure may also be present near New Braunfels.

INTRODUCTION

The Balcones fault zone is a tensional structural system consisting of numerous normal faults, cross faults, grabens, horsts, step faults, en echelon faults, and similar features in central and south Texas. The fault zone extends from Waco southward to Austin and San Antonio and then westward to Del Rio. Generally, the rocks exposed at the surface west of the fault zone are Lower Cretaceous stratigraphic units consisting of resistant limestones, dolomites, and marls; east of the zone, the rocks exposed are Upper Cretaceous nonresistant chalk and calcareous clay units. The difference in resistance to erosion has resulted in a fault-line scarp known as the Balcones Escarpment. Soils east of the scarp are deep and well developed, and the predominant historical agricultural land use has been for cropland. West of the scarp, the soils are thin and rocky, and ranchland is the the predominant agricultural land use.

The Balcones Escarpment and fault zone are especially well developed in the area around San Marcos, Texas about 35 miles south of Austin. The purpose of this paper is first to describe the structural style in a case study area between two major en echelon step fault systems and then to set forth hypotheses on geomorphologic and groundwater implications of the zone of adjustment between these en echelon fault systems. The discussion of structural style and resulting outcrop patterns is based upon detailed geologic mapping for environmental geologic purposes in two 7-1/2 minute topographic quadrangles in the rapidly growing San Marcos area (Grimshaw, 1976).

The principal features of the case study area, besides the city of San Marcos, are Interstate 35, the town of Kyle, the Blanco River, Purgatory Creek, Sink Creek, San Marcos Springs, and the San Marcos River (Figure 1).

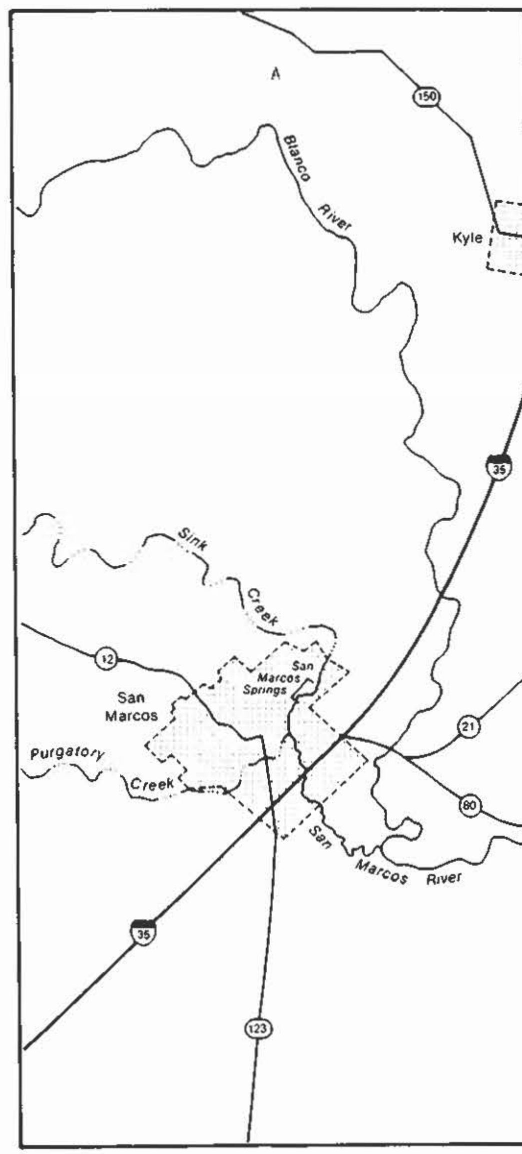

Figure 1. Principal Features Of The San Marcos Case Study Area.

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GEOLOGIC OVERVIEW

A generalized geologic map of the San Marcos area is shown in Figure 2. The principal rock-stratigraphic units in the area, in descending stratigraphic order, are shown below. All are Cretaceous in age.

Unit	Approximate Thickness (ft)
Taylor Group (clay)	925
Austin Group (chalk)	170
Eagle Ford Formation (clay)	25
Buda Formation (limestone)	50
Del Rio Clay	50
Georgetown Formation (marl)	33
Edwards Group (limestone)	475

Major faults of the Balcones system traverse the study area from northeast to southwest. The net displacement in the case study area, as elsewhere in the Balcones fault zone, is downward to the southeast. The faults of major displacement strike about N30 E. The Edwards Limestone crops out over most of the area west and north of these faults, and the Austin chalk and Taylor clay compose the subsurface east and south of the faults. Outcrops of the thin intervening formations between the Edwards and Austin occur in numerous fault blocks within the fault zone.

The regionally important Edwards aquifer is especially significant in the San Marcos area, both as an essential source of copious fresh water and as a recreational resource associated with San Marcos Springs. These springs are a major discharge point of the Edwards aquifer; discharge averages about 161 million gallons per day. The extensive outcrop area of the Edwards limestone in the western and northern portions of the area is an important part of the aquifer recharge zone.

The Balcones fault zone enters the northeastern part of the case study area as two major step faults -- Mustang Branch fault and Mountain City fault (Figure 2). These faults are referred to hereafter as the "northeastern step fault zone". The Kyle fault, located farther to the southeast, is another step fault in this succession. Similarly, the Balcones fault zone is represented in the southwest part of the area by three major step faults -- Comal Springs fault, San Marcos Springs fault, and Bat Cave fault, referred to hereafter as the "southwestern step fault zone". The major northeastern and southwestern step fault zones are thus in en echelon relationship across the study area.

The fact that fault traces are not at all influenced by topography indicates that all faults are vertical or nearly so.

STRUCTURAL INTERPRETATION

The cumulative displacement across the northeastern step fault zone generally decreases to the southwest. Similarly, cumulative displacement across the southwestern step fault zone decreases to the northeast. Thus, the total displacement downward to the southeast remains relatively constant across the study area, but is "transferred" from the northeastern to the southwestern step fault zone as is typical for en echelon fault zones in a tensional fault system like the Balcones.

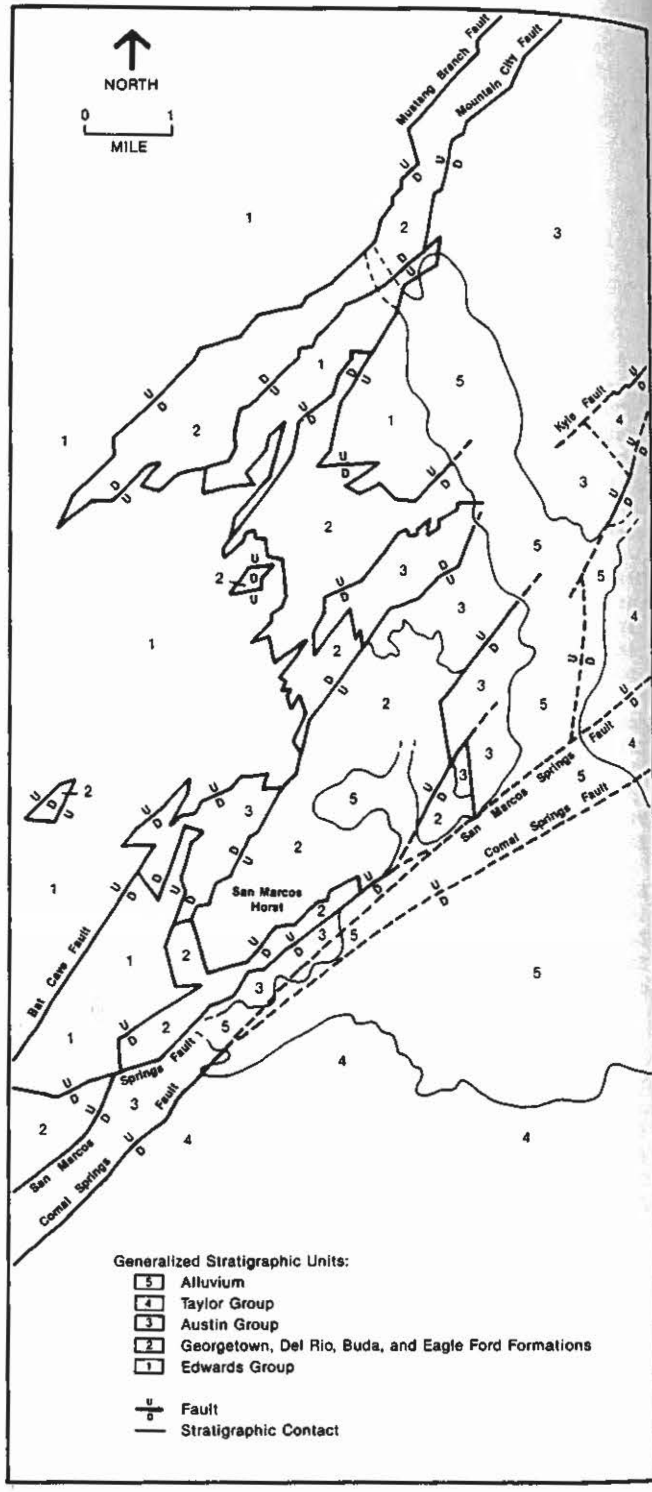

Figure 2. Simplified Geologic Map Of San Marcos Area, Showing Step Fault Zones and Associated Faulting In The Area Between.

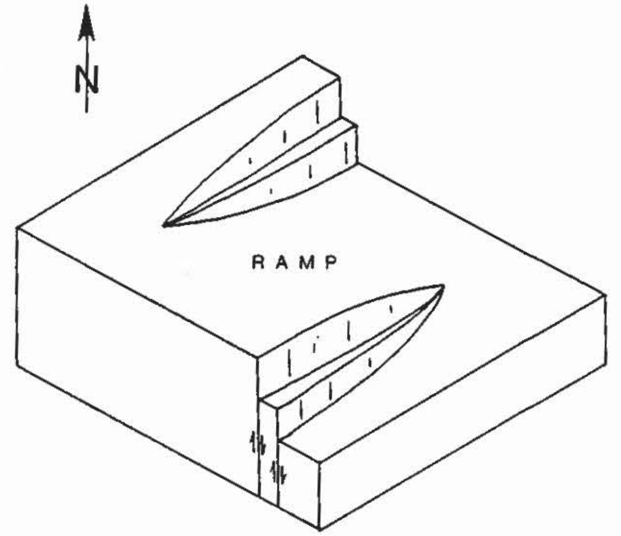

Figure 3. Block Diagram Of En Echelon Step Fault Zones Showing Intervening Ramp Structure.

The transfer of displacement between the step fault zones is shown in block diagram form in Figure 3. The area of adjustment between the step fault zones forms a ramp-like structure which bends downward to the northeast from the upthrown side of the southwestern step fault zone to the downthrown side of the northeastern step fault zone. If this ramp were eroded to a level surface parallel to the bottom of the block in the diagram, an outcrop pattern with older rock units exposed in the southwest and successively younger units exposed to the northeast would be displayed. Just such a pattern is exhibited in the case study area, where Edwards limestone exposures in the southwest part of the area, on the upthrown side of the southwestern fault zone, give way northeastward to Austin chalk and Taylor clay bedrock on the downthrown side of the northeastern step fault zone.

The ramp structure is broken up into several irregularly shaped grabens, horsts, and step fault blocks which are, in turn, broken up into numerous small, irregular fault blocks as small as 100 yards (or less) in dimension as shown in Figure 4. The overall structural grain of the faulting in the ramp is consistent with the regional Balcones fault zone, with the larger-displacement faults having a northeastward orientation, but with the smaller cross faults oriented in all directions.

The geometry of the larger grabens and horsts, as well as the much smaller individual fault blocks within them, suggests that the ramp was subjected to some torsional stresses, in addition to the dominant tensional stresses, as the southeastern part of the area "dropped away" from the northwestern part and the ramp area adjusted to the transfer of displacement from the northeastern to the southwestern step fault zone.

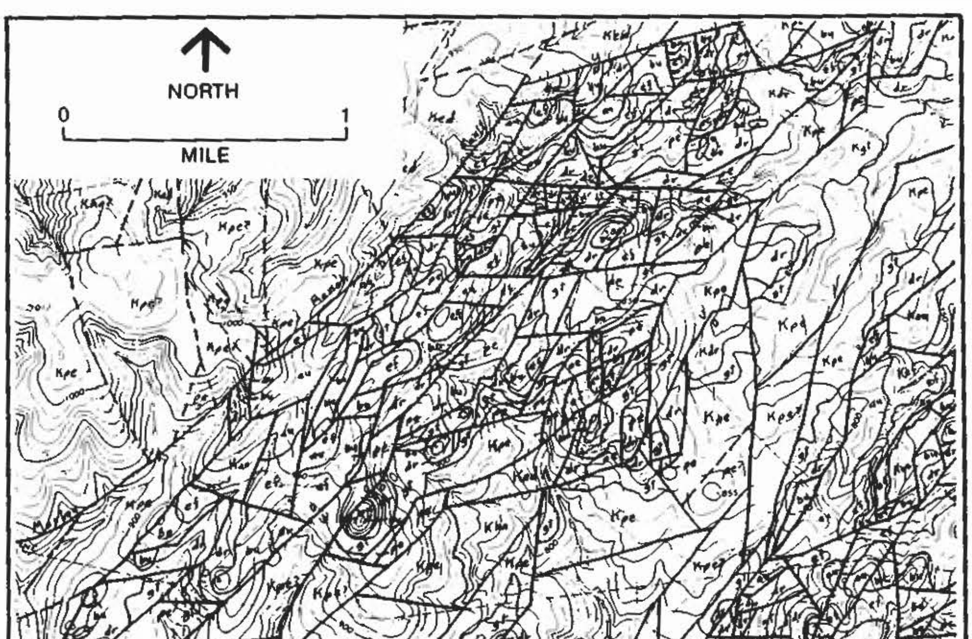

Figure 4. Detail From Geologic Map Of San Marcos Area, Showing Intensity Of Faulting In The Ramp Structure Area (from Grimshaw, 1976).

The resulting overall outcrop pattern, with the Edwards giving way to the Austin and Pecan Gap northeastward along the ramp, and with the complex, irregular faulting between the en echelon step fault zones, is shown clearly in Figure 2. The intervening units between the Edwards Limestone and the Austin Chalk are exposed in the complexly faulted area extending generally southward from the northeastern step fault zone to the southwestern step fault zone. The outcrop pattern on a larger scale and in more detail is a mosiac of irregular fault block outcrops having an appearance not unlike a shattered pane of glass (Figure 2). The complex faulting of the ramp into irregular grabens and horsts at the smaller scale (Figure 3), and the small, irregular fault blocks at the larger scale (Figure 4), represent the adjustment of the ramp area to the tensional and lesser torsional stresses during the Balcones faulting.

The intensity of faulting depicted in Figure 4 is most clearly displayed in the band of outcrops of intervening stratgraphic units between the Edwards limestone and the Austin chalk in the graben and horst area between the en echelon step fault zones. It is likely that this intensity of faulting also exists in the areas of exposure where the Edwards, Austin, and Taylor Groups are exposed, but the lithologic homogeneity of these units does not allow the individual fault blocks to be mapped in such detail. It is only where the succession of thin, lithologically dissimilar units represented by the Georgetown (marl), Del Rio (clay), Buda (limestone), Eagle Ford (clay with thin siltstone layers) is affected by the intense faulting that sufficient stratigraphic control allows the very small individual fault blocks to be mapped.

Along the northeastern section of the southwestern step fault zone there is a major, high-standing fault block, herein named the San Marcos horst, which is undisturbed by the intricate faulting that characterizes most of rest of the area northwest of the step faults. The cause of this large, undisturbed, monolithic fault block remains problematical. The Balcones Escarpment is especially well developed along the eastern margin of this horst; the Old Main building of Southwest Texas State University is built on this prominent scarp and is a striking local landmark which is easily seen by travelers on nearby Interstate 35. Much of the western half of San Marcos is built on this large fault block, and San Marcos Springs discharges along its northeastern margin.

POTENTIAL GEOMORPHOLOGIC IMPLICATIONS: A HYPOTHESIS

Woodruff (1977), in a discussion of development of drainage patterns near the Balcones Escarpment, has shown that the Blanco River formerly discharged into what is now the Onion Creek drainage basin. The "elbow" in the course of the Blanco River in the northern part of the case study area is near the point at which a headward eroding smaller stream captured the Blanco and diverted its flow from generally eastward to a southeastward direction. The point designated "A" in Figure 1 is the location of a distinctive erosional feature which is interpreted to be a former channel of the pre-capture course of the Blanco. This feature is now located on the drainage divide between the Blanco River and Onion Creek drainage basins.

Not long after Balcones faulting occurred (currently believed to be during the Miocene), the stratigraphic units exposed in the vicinity of the en echelon faults and associated ramp structure in the study area were Upper Cretaceous or younger. It may reasonably be expected that as erosion occurred and the land surface lowered in the area, the more resistant Austin chalk was exposed in the southwestern part of the ramp structure while the less resistant Taylor clay was still present in the northeastern part of the structure. Further, because of marked difference in erodibility of these units, it may be expected that a small east-facing escarpment would have formed along the ramp.

The hypothesis or question then arises, "Could this small escarpment then have determined the course of the stream which ultimately captured the Blanco River?" If the answer is in the affirmative, then the physiographic development in the area was controlled by the presence of the en echelon faulting and associated ramp, and the present southeasterly course of the Blanco was ultimately determined by the presence of the ramp.

POTENTIAL HYDROLOGIC IMPLICATIONS: ANOTHER HYPOTHESIS

Woodruff and Abbott (1979) have hypothesized that the current principal discharge points of the Edwards aquifer, such as San Marcos Springs and Comal Springs, have developed at or near the locations where major streams and rivers traverse the Balcones Escarpment. In effect, these locations represent the lowest elevation points where the Edwards limestone is exposed. There, the actively downwardly eroding rivers have opened drains for the aquifer.

After the Blanco River was captured into its current southeastward course, its grade was increased and the currently visible deeply incised canyon where the river crosses the Edwards limestone was formed. This canyon opens to a wider valley containing alluvium at the point where the river crosses a fault and begins to flow on outcrops of younger strata, primarily the Austin chalk (Figure 2). The valley widens again, this time to a much greater extent, at the point farther downstream where the river begins to flow on the Taylor Clay.

Although the river is still downcutting after it passes out of the Edwards, it is also effectively sidecutting as evidenced by the presence of alluvium in the valley in this stretch. The continued downcutting is indicated by the presence of bedrock exposures in the river channel. The thickness of the alluvium and the presence of a single sequence of fining upward grain size pattern in the alluvium indicate that the river is removing and redepositing its alluvial deposits as it shifts course in its valley.

The question naturally arises: "Was the Blanco River responsible for cutting a drain into the Edwards aquifer at the current location of San Marcos Springs?" The current locations of the river, the springs, and Sink Creek indicate that if the Blanco did open this discharge point of the aquifer by downcutting or sidecutting at the location of the springs, it occurred many years ago when the land surface and the river were at somewhat higher elevation than at present.

If the hypotheses outlined above and in the previous section are correct, then the current location of San Marcos Springs was determined by the presence of the Blanco River, whose location was in turn determined by the northeastern and southwestern en echelon step faults and the associated ramp structure. The role of the San Marcos horst in this sequence of events awaits further study.

POSSIBLE SIMILAR STRUCTURAL PATTERNS ELSEWHERE IN THE BALCONES FAULT ZONE

Inspection of maps of the Geologic Atlas of Texas published by the University of Texas Bureau of Economic Geology (Barnes, 1974a, 1974b, 1974c) suggests that similar structural patterns exist elsewhere in the Balcones fault zone. For example, a similar ramp structure is indicated in the Austin area, where outcrops of Edwards limestone in an en echelon step fault setting give way northeastward to Austin chalk outcrops. A band of outcrops of Georgetown, Del Rio, Buda, and Eagle Ford Formations extends southward from the Colorado River to the town of Buda. This band separates Edwards outcrops to the southwest from Austin chalk outcrops to the northeast, just as in the San Marcos area.

A smaller scale but similar pattern may also exist near New Braunfels, where outcrops of Edwards limestone gives way northeastward to Austin chalk outcrops in an apparent ramp structure, with a transition zone of Del Rio, Buda, and Eagle Ford Formation outcrops between.

Southwest of New Braunfels, the en echelon faulting in the Balcones fault zone reverses, with major displacement shifting from southeastward fault zones to northwestward fault zones. Ramp structures in this area are thus also reversed, with bending downward to the southwest rather than to the northeast as in the San Marcos area. One such "reversed" ramp structure, where Edwards outcrops give way southwestward to Austin chalk outcrops, and with intervening exposures of Georgetown through Eagle Ford fault blocks, is apparent immediately northwest of San Antonio. Another larger one appears to be present across most of Media County and far eastern Uvalde County.

SUMMARY

Detailed geologic mapping of intensely faulted Cretaceous strata in the Balcones fault zone in the San Marcos area has revealed a structural style and bedrock geometry which have potential implications for the geomorphologic and hydrologic development of the area.

The current location of the Blanco River and San Marcos Springs may have resulted from a sequence of events whose course was determined by this structural style and the relative resistance of the Cretaceous units to erosion. The presence of the two en echelon step fault zones and associated ramp structure may have been the ultimate cause of both the current, captured course of the Blanco River and subsequently the location of San Marcos Springs.

Similar en echelon structural patterns with ramps are indicated in at least three other locations in the Balcones fault zone.

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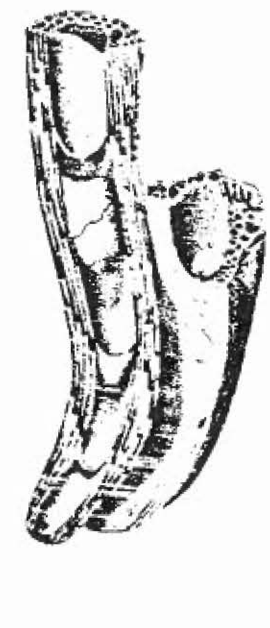
TOUCASIA

MONOPLEURA



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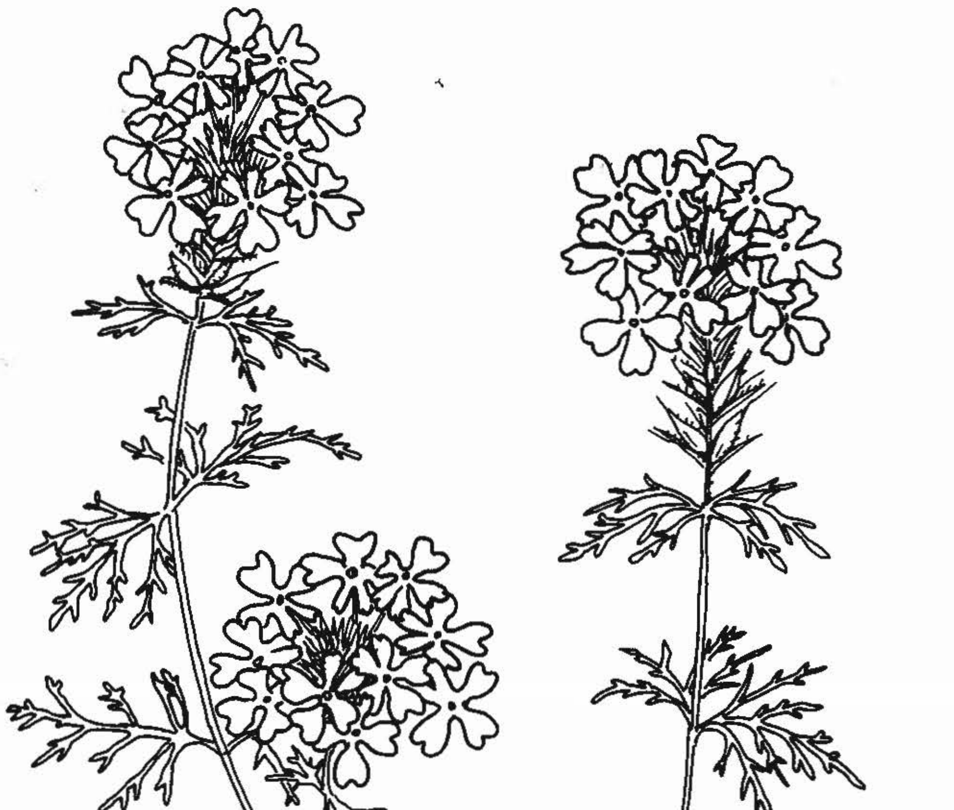

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STREAM PIRACY AND EVOLUTION OF THE EDWARDS AQUIFER ALONG THE BALCONES ESCARPMENT, CENTRAL TEXAS

C.M. Woodruff, Jr.
Consulting Geologist
P.O. Box 13252
Austin, TX 78711

Patrick L. Abbott
Department of Geological Sciences
San Diego State University
San Diego, CA 92182

INTRODUCTION

Three river systems dissect the southern margin of the Edwards Plateau in south-central Texas: the Nueces, the San Antonio, and the Guadalupe (Fig. 1). The Edwards Plateau is a karstic upland, and its dissected margin consists of plateau outliers, narrow incised stream courses, and intervening areas of steeply sloping terrain known locally as the Central Texas Hill Country.

The upper reaches of these three drainage basins constitute an important hydrogeologic entity; they include the catchment watersheds, the recharge areas, and the points of discharge for the central segment of the Edwards artesian aquifer. The Edwards aquifer is a major cavernous limestone system that extends for over 400 km along the Balcones fault zone from Val Verde County on the Mexican border to Bell County in north-central Texas (Fig. 1). The central part of the aquifer is the most prolific water-yielding segment and thus is the main focus of this report; it constitutes the main water supply for a region that includes the city of San Antonio and a population of more than one million people. Some attention also will be given to the 390 km^2 Barton Springs segment that lies immediately north of the central aquifer segment.

Major exchanges on a regional scale occur between surface stream flow and groundwater levels in the central segment of the aquifer (Sayre and Bennett, 1942; Pettit and George, 1956; Arnow, 1963; Klemt and others, 1975; Woodruff and Abbott, 1979). In brief, most recharge occurs within the semiarid western part of this aquifer segment, while most discharge occurs in the subhumid eastern portion. Interactions between the surface and subsurface water regimes are likely to have occurred during earlier developmental stages of both the aquifer and the surface drainage network. It is our purpose to show that drainage-basin evolution and aquifer development have operated mutually. That is, within larger structural geologic and climatic controls, physiographic development near the Balcones fault zone predetermined both geographic configuration and magnitudes of recharge and discharge in the Edwards aquifer. Moreover, aquifer development has influenced the evolution of surface drainage configurations by the diversion of surface flow via recharge in one area while augmenting stream flow via spring discharge elsewhere. We propose that these relations are due in large measure to stream piracy that chiefly occurred within the San Antonio and Guadalupe watersheds. Similar piracy also affected landform and hydrologic development farther north within the Barton Springs segment of the Edwards aquifer (Woodruff, 1984a).

Stream piracy greatly increased the catchment area of the through-flowing Hill Country rivers where they cross resistant limestone strata within the fault zone (Woodruff, 1977; Woodruff and Abbott, 1979). The higher average rainfalls that occur in the pirated basins also enhance the ability of these streams to cut deep canyons. Deeply incised canyons were necessary to provide spring sites for groundwater that otherwise would have been trapped and then equilibrated chemically with host rocks and therefore would have ceased the dissolution of the surrounding limestones (Abbott, 1975). If piracy had not occurred, the dynamic hydrologic situation would not have developed as rapidly and the formation of cavernous porosity would have been retarded. As it happened, a region-wide circulation system developed during two diverse time periods. The first was near the middle of the Cretaceous Period when the Edwards Limestone was deposited, exposed subaerially, and buried. The second was during the Miocene Epoch when Balcones faulting occurred, and the erosion of the fault-rejuvenated streams exhumed the Edwards Limestone. Eventually, extensive cavern systems developed as the main conduits for transmission of groundwater.

GEOLOGIC SETTING

The structural and stratigraphic frameworks of the study area are the basic controlling factors for both surface and subsurface drainage development. Most aquifer development occurred within rocks of the Edwards Group that were deposited on the San Marcos platform and in the Edwards-equivalent limestones of the Devils River trend (Fig. 1).

The stratigraphic and lithic characteristics of the (Albian Stage) Edwards Limestone originated with the differing depositional environments, and resultant facies, of late Early Cretaceous time. To summarize Rose (1972), the San Marcos platform acted as an area of lesser subsidence during the time of Edwards deposition. That platform was the site of accumulation of about 150 m of shallow marine and tidal flat sediments. At the same time along the Devils River trend roughly a 300 m thickness of grainstone and rudist boundstone was formed. Subsequent uplift along the northwest-trending axis of the San Marcos platform caused more than 30 m of the uppermost Edwards Group to be removed by erosion during late Early Cretaceous time (Fig. 2). Subaerial erosion of carbonate rock was accompanied by pore-space enlargement and cavern development resulting from circulation of shallow meteoric waters. The part of the Edwards Group that makes up the present aquifer in Bexar, Comal and Hays Counties--(where discharge dominates today)-- was on the San Marcos platform and received significant

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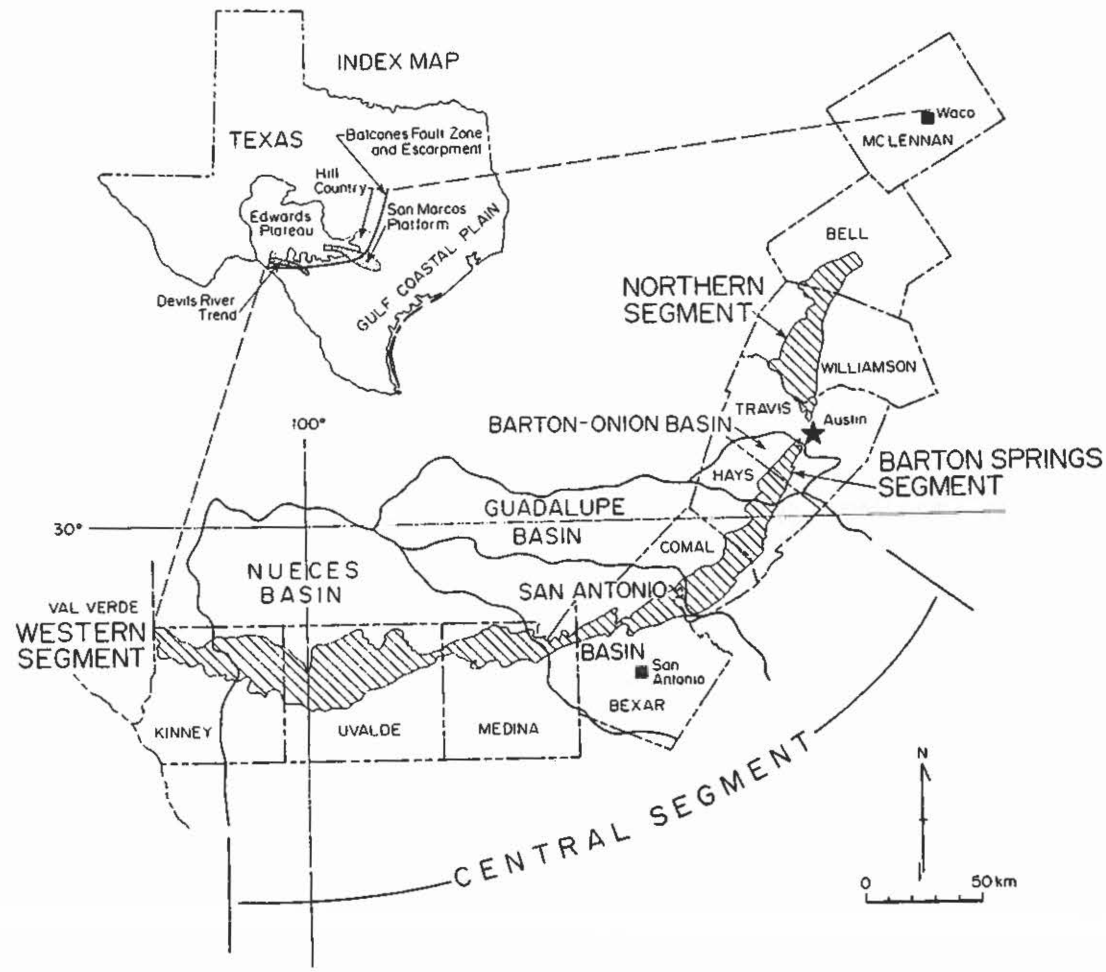

Figure 1. Location of the Edwards Aquifer in relation to the Balcones fault zone and other physiographic features. Note how the Aquifer cuts across the surface drainage basins.

enhancement of porosity during Cretaceous time. The parts of the aquifer in Medina, Uvalde and Kinney Counties-- (where recharge dominates at present)-- were southwest of the axis of uplift and apparently received little, if any, solution enlargement of porosity during Cretaceous time. During the remainder of the Early Cretaceous and throughout Late Cretaceous time the entire region was covered by shallow marine shelf waters. Deposition of argillaceous and micritic sediments resulted in the Edwards Group being covered on the San Marcos platform by a 260 m thickness of low-permeability rocks. This burial sealed off the Edwards Group and precluded the circulation of ground- water necessary to further increase porosity.

At about the end of the Cretaceous, slow upwarping of the northwestern margin of the subsiding Gulf of Mexico basin lifted the region of the present-day Edwards aquifer above sea level. Continued deformation gave a generally southeastward dip to the sedimentary rock units of central and south Texas. At this time, deep groundwater might have augmented earlier developed porosity except this groundwater system would have been largely static, having no means for egress (Abbott, 1975). This stasis would have resulted in chemical equilibration between host rock and the waters contained therein, thus preventing extensive cavern development at that time.

The dominant geologic feature in the region is the Balcones fault zone, a system of en echelon, mainly down-to-the-coast, normal faults that extend about 545 km from Del Rio on the Mexican border to near Waco in north-central Texas. Faulting probably occurred primarily during the late Early Miocene (Young, 1972), as evidenced by the abundance of reworked Cretaceous fossils and limestone fragments in the fluvial sandstones (calclithite) of the Oakville Formation (Wilson 1956; Ely, 1957). The strike of individual faults within the study region is predominantly northeast-southwest, but the overall structural alignment subtly changes to a more east-west trend in the southwestern part of the region. Faulting within the San Antonio, Guadalupe, and Colorado River basins has juxtaposed the approximately 150 m-thick Edwards Limestone against the older Cretaceous Glen Rose Formation which consists largely of alternating beds of limestone, dolomite, and marl. On the downthrown (eastern) side throughout the region the Edwards Limestone abuts against less resistant chalk, clay, and marl units of younger Cretaceous age.

Displacement along the main fault-line scarp is as little as 60 m in the westernmost part of the region, whereas a maximum displacement of about 185 m occurs in the Guadalupe River basin (Klemt and others, 1975). Similarly, total stratigraphic

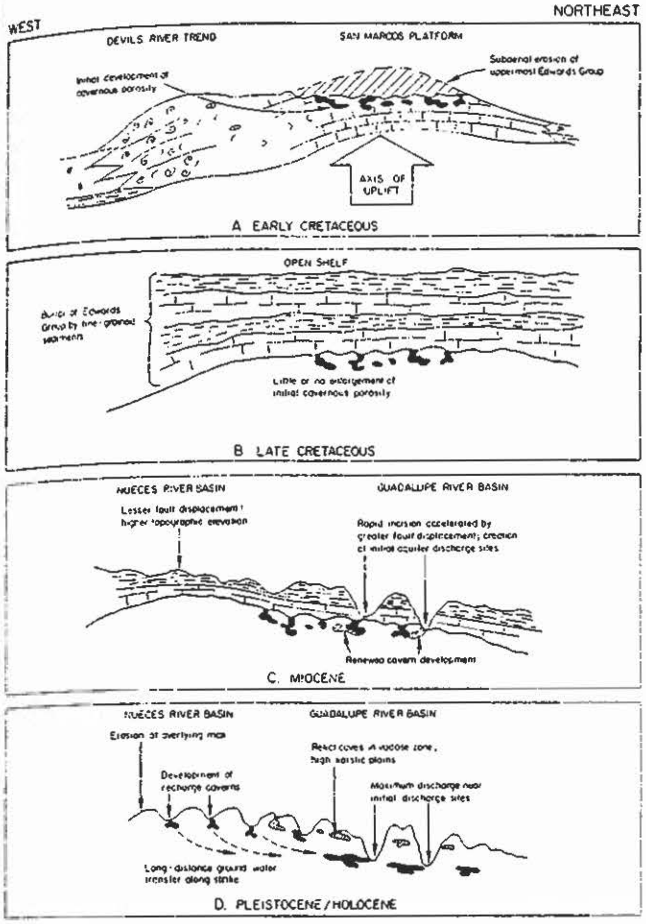

Figure 2. Schematic cross sections of stages in the development of the Edwards Aquifer (modified from Rose, 1972, and Abbott, 1975).

displacement decreases from east to west. Total displacement in Comal County is as much as 520 m over a maximum width of 39 km (George, 1952). This fault-bound exposure of limestone has resulted in compartmentalization of the aquifer into a narrow belt that includes most of the recharge and discharge areas within the eastern basins. Farther west, however, in Uvalde County, total displacement is only 215 m (Welder and Reeves, 1962). Because of this lesser fault displacement, the aquifer is not confined to a narrow outcrop belt (Barnes, 1974a, b, c). Instead, the Edwards Limestone crops out continuously across much of the Nueces basin, and thus can receive recharge waters through a larger area than in the San Antonio or Guadalupe watersheds.

PHYSIOGRAPHIC SETTING

The most evident geologic controls on the physiography of the region include the topographic changes across the main line of displacement of the Balcones fault zone. There, an escarpment separates the low-relief terrain of the Gulf Coastal Plain from the ruggedly dissected Hill Country to the north and west (Fig. 3). The orientation of the escarpment changes from northeast/southwest in the Guadalupe, San Antonio and Colorado River watersheds to a more east-west trend in the Nueces River watershed. In response to these changes in relief and in orientation, the topographic position and geometry of drainage nets also change from west to east. The highest topographic elevations occur in the headward reaches of the westernmost part of the Nueces watershed. Likewise, the component rivers of the Nueces system cross the Balcones escarpment at generally higher elevations than do streams within the San Antonio and Guadalupe basins. The escarpment is less pronounced in the Nueces basin where fault displacement is less and where streams trend throughout their entire upper courses in a generally southward direction. The most extensive alluvial plains exist south of the main fault line in the Nueces basin rather than in the areas near the escarpment to the northeast (Barnes, 1974b). Moreover, streams of the Nueces system have generally broader alluvial valleys throughout their reaches, despite the fact that they transect large outcrop areas of resistant limestone strata. Yet, studies by Rose (1972) show the overall properties of the limestones within these western basins to be similar to rocks occurring in those parts of the San Antonio and Guadalupe basins where steep-walled canyons have been eroded, and where little or no alluviation has occurred.

Stream regimes also change in the vicinity of the Balcones fault zone. Upstream from the fault zone there are moderately wide alluvial valleys separated by broad interfluves consisting of plateau remnants. Within the fault zone, streams are incised as narrow canyons into the resistant limestone strata. Little or no alluvial deposits occur within these incised reaches. Immediately downstream from the Balcones escarpment, broad alluvial plains occur that have both modern depositional surfaces associated with active streams as well as high relict deposits blanketing uplands far from present fluvial activity.

Medina River, Cibolo Creek, and Guadalupe and Blanco Rivers display a distinctive geometric response to geologic controls near the Balcones fault zone. These streams flow in their upper reaches in a roughly eastward direction, the projection of which is at an acute angle to the strike of Balcones faulting. Where these streams cross the resistant limestone in the fault zone there is an abrupt change in course to a trend roughly perpendicular to the fault-line scarp. Associated with these abrupt elbow turns is incision into steep- walled canyons within the resistant limestone. Asymmetrical drainage basins also occur, and there are relict erosional and depositional features on drainage divides near the elbow turns. Woodruff (1974, 1977) has postulated that stream piracy occurred in these reaches of the San Antonio and Guadalupe basins as a result of streams with steeper gradients eroding normal to the Balcones fault zone. Similar features and processes have been noted in the Barton Creek watershed (Woodruff, 1984) and farther north near the Jollyville plateau (Woodruff, 1985). No piracy of such large magnitude is evidenced in the Nueces basin; there are no elbow turns, asymmetrical basins, or relict fluvial features on divides between major streams. Thus, it is presumed that component streams of the Nueces system have flowed generally southward throughout their developmental history.

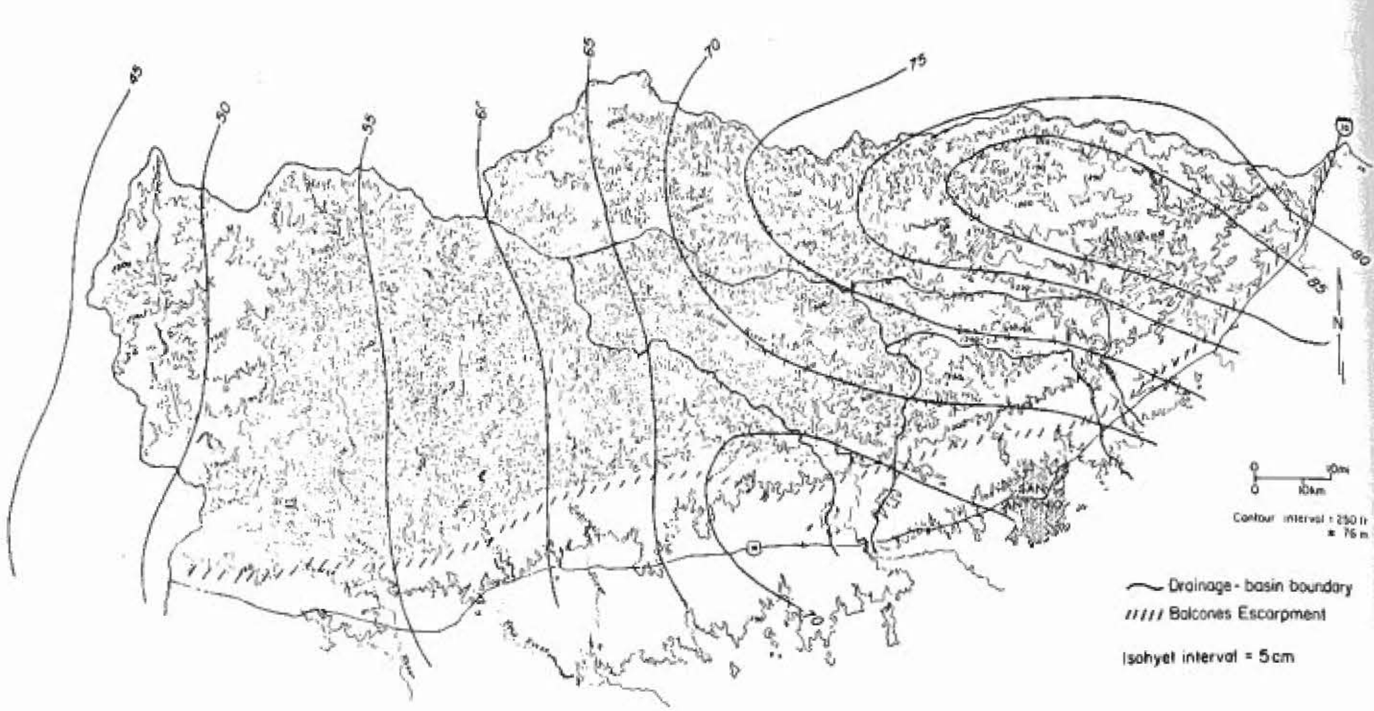

Figure 3. Topography and rainfall of the central segment of the Edwards Aquifer (modified from Woodruff and Abbott, 1979).

CLIMATIC SETTING

Besides bedrock conditions, another controlling factor affecting water regimes and landform development is climate. In the western part of the region the climate is semiarid, with mean annual rainfall as low as 48 cm in some areas (Fig. 3). This, coupled with high evaporation rates, means that streamflow and erosional potential of western streams are necessarily lower than that of the subhumid eastern basins. The Guadalupe River basin, for example, lies in the center of an oblong 80-cm isohyet, whereas the 50-cm isohyet follows the West Nueces River (Fig. 3).

Climatic differences are especially reflected in magnitudes of streamflow. For example, Guadalupe River, draining 3,932 km^2 where it crosses the Balcones escarpment, has a mean flow of 10.54 m^3/s. This is about three times larger than the combined discharge of the Nueces and West Nueces Rivers where they flow together south of the fault zone; they have a watershed of 5,043 km^2 with a mean discharge of 3.12 m^3/s. However, these values reflect water losses caused by infiltration into the aquifer by streams of the Nueces River system above and beyond those owing to rainfall deficiencies or increased rates of evaporation. Comparing stream gage date upstream and downstream from the fault zone, it is seen that where the East and West Forks of the Nueces River converge below the recharge zone their basin areas increase 74 percent while their mean total discharge decreases 59 percent (U.S. Geological Survey, 1974). No such recharge loss is included in the Guadalupe River water budget. These differences between the Guadalupe and Nueces flow regimes demonstrate the self-ramifying conditions that are evident in many limestone aquifers. Where water is maintained predominantly in surface flow, more stream erosion and thus incision can occur. Where water infiltrates underground, not only is there a lessened amount available to perform surface erosion, but, because of soluble bedrock, these recharging waters enlarge their flow paths, thus ensuring further underground infiltration.

HYDROLOGIC SETTING

The Edwards aquifer consists of two components--an unconfined (water-table) aquifer in the plateau lands and Hill Country upstream from the main fault-line scarp of the Balcones fault zone, and a confined (artesian) aquifer within the eastern and southeastern part of the fault zone. Recharge to the water-table aquifer results from precipitation occurring throughout much of the Edwards Plateau; this catchment area extends beyond the drainage basins composing this study region (Fig. 4). Groundwater beneath the Edwards Plateau moves mainly toward the southeast down the regional dip of the aquifer; part of this water discharges through myriad seeps and springs that provide base flow for headwater streams in the Nueces, San Antonio, Guadalupe, and Colorado River basins. Surface streams sustained by this spring-derived base flow eventually cross the highly fractured, cavernous limestones in the Balcones fault zone. There, infiltration into the confined aquifer occurs. In addition, about 6 percent of the recharge into the Edwards occurs by underflow from adjacent rock units such as the Glen Rose Formation. This recharge moves directly into the confined aquifer without having been discharged first as surface flow (William B. Klemt, writ. comm., 1977).

Major recharge occurs in two types of terrane--stream bottoms underlain by faulted or cavernous limestone, and low-relief uplands underlain by karstic limestones. The more important of the two recharge areas is where stream courses cross

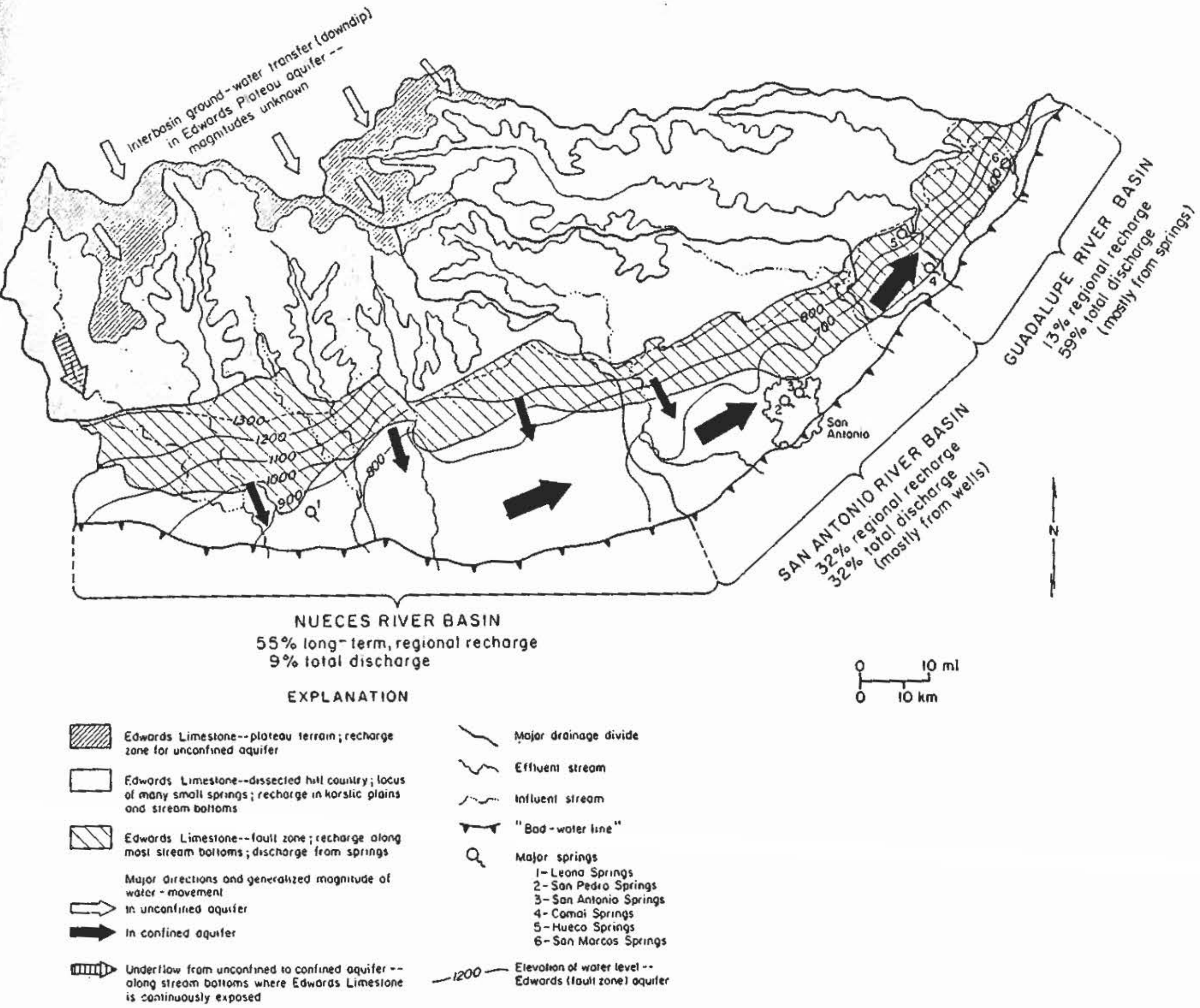

Figure 4. Recharge-discharge relations and potentiometric levels, central segment of the Edwards Aquifer (modified from Woodruff and Abbott, 1979).

permeable limestone. Water-budget studies in the Barton Springs segment of the aquifer have shown that about 85 percent of incident rainfall is cycled through evapotranspiration, about 9 percent runs off, and the remaining 6 percent recharges the aquifer. Of the recharge fraction, about 85 percent occurs within stream bottoms (Slade, 1984; Woodruff, 1984b). Recharge zones along bottomlands are especially apparent because stream discharges decrease through these reaches, dry or nearly dry stream beds commonly are incised into bedrock and there is a concomitant attenuation of alluvial deposits. About 55 percent of the estimated annual recharge into the central segment of the confined aquifer is supplied by the component streams of the Nueces basin (Fig. 4). Most natural discharge occurs from springs along the Balcones escarpment--notably from Comal Springs and San Marcos Springs. Most well discharge occurs in the San Antonio area, and well pumpage is increasing with growing population demands. Total discharge from wells now often exceeds total discharge from springs (Klemt and others, 1975). In the eastern part of the central aquifer segment the yields from water wells are greater, discharge from springs is more voluminous, and water levels tend to fluctuate more uniformly, compared to aquifer-discharge characteristics farther west (Table 1). These observations imply that cavernous porosity is best developed near the distal end of the groundwater flow system in the areas farthest removed from the major loci of recharge. The same relations are seen in the smaller Barton Springs segment(Slade, 1984). Furthermore a county-by-county enumeration of vadose caverns conducted by the Texas Speleological Survey documents an increase in the number of caves from west to east along the Balcones fault zone. As of August, 1977, there were 22 surveyed caves in Kinney County, 63 in Uvalde County, 39 in Medina County, 81 in Bexar County, 92 in Comal County, and 86 in Hays County. Thus, caves surveyed in the recharge zone number 123 compared to 259 in the discharge end of the fault zone (R. Fieseler, writ. comm., 1977).

Similarly, caverns have been shown to be major conduits for groundwater flow in at least part of

Table 1. Long-term recharge and discharge from central segment of the Edwards artesian aquifer.

(Data from unpublished U. S. Geological Survey source, The Edwards Underground Water District, and the Texas Department of Water Resources)

	RECHARGE				DISCHARGE						
					Springs				Wells		
	Basin Area km^2	Mean Annual hm^3 (1934-1971)	Extremes (hm^3) High (Year)	Extremes (hm^3) Low (Year)		Mean Annual hm^3 (period of record)	Extremes (hm^3) High (Year)	Extremes (hm^3) Low (Year)	Mean Annual hm^3 (1934-1971)	Extremes (hm^3) High (Year)	Extremes (hm^3) Low (Year)
NUECES RIVER SYSTEM											
Nueces/West Nueces River	5,043	124.3	507.1 (1935)	10.6 (1934)	Leona Springs	24.9 (1963-1975)	54.3 (1973)	+			
Interfluve: Nueces/Dry Frio	91	insig.									
Frio/Dry Frio Rivers	1,712	112.4	369.9	5.2							
Interfluve: Frio/Sabinal	142	insig.									
Sabinal River	640	39.9	275.9 (1958)	0.7 (1955)							
Interfluve: Sabinal/Medina	1,228	75.1	363.6 (1958)	4.4 (1956)							
Subtotal, Nueces System	8,856	369.2				24.9			38.6	159.5 (1971)	5.1 (1934)
SAN ANTONIO RIVER SYSTEM											
Medina River	1,738	63.9	128.2 (1960)	7.8 (1956)							
Interfluve: Medina/Cibolo	813	71.0	235.4 (1958)	2.5 (1956)	San Pedro/San Antonio Springs	16.2 (1963-1975)	67.2 (1963)	+			
Cibolo Creek	710	82.6*	311.8 (1957)	1.5 (1956)							
Subtotal, San Antonio System	3,261	217.5				16.2			212.8	321.6 (1971)	118.0 (1934)
GUADALUPE RIVER SYSTEM											
Dry Comal Creek	337	46.8*	178.8 (1957)	0.4 (1955)	Comal Springs	250.8 (1928-1974)	476.7 (1973)	insig. (1956)			
Guadalupe River	3,932	insig. · · · · · · · · ·			Hueco Springs	32.7 (1944-1974)	116.9 (1968)	+			
Blanco River	1,311	39.4	94.2	1.4	San Marcos Springs	143.8 (1956-1974)	143.8 (1973)	41.1 (1956)			
Subtotal, Guadalupe System	5,580	86.2				427.3			7.6	20.5 (1971)	2.5 (1937)
TOTAL	17,697	672.9				468.4			259.0		
					Total Mean Annual Discharge	727.4					

\+ Numerous Periods of No Flow
* Period of Record 1954-1973

the artesian aquifer. Blind catfish have been found in waters discharged from wells as deep as 610 m in the San Antonio area (Hubbs, 1971). A notable cave fauna also exists in the waters of San Marcos Springs (Upa and Davis, 1976; Holsinger and Longley, 1980).

QUESTIONS AND HYPOTHESES

There are anomalies in this regional hydrologic picture. The drier western areas subsidize (by recharge) the water supplies for the areas with higher perennial rainfall and streamflow. Evidently, topography is one main control of the recharge-discharge couplet; recharge occurs primarily at higher elevations such as occur in the Nueces Basin and discharge occurs mainly at low points. Moreover, the total catchment area of the component streams in the Nueces basin represents 49 percent of the areas of the three major basins of the region. A much larger drainage-catchment area plus a base flow augmented by spring discharge from the unconfined aquifer on the Edwards Plateau, apparently compensates for a decrease in precipitation in these westernmost basins.

But why has erosion been less in the Nueces watershed? Why was there an initial impetus for transfer of water from the semiarid west to the subhumid eastern part of the region? Why does the largest single, integrated basin in the region (the Guadalupe River) contribute insignificant amounts of recharge where it crosses the fault zone? Why did the eastern river systems incise more vigorously into lower topographic levels to create initial discharge sites that controlled aquifer development while the Nueces basin was left "high and dry?"

The hypotheses posed here are that present surface drainage conditions, aquifer recharge-discharge relations, and direction of potentiometric gradient can be explained by several geologic determinants and by the activity of processes that have occurred as a result of these determinants.

Fracturing and displacement of pre-existing strata set into motion the overall drainage evolution of the region. These structural events affected rocks that, in turn, reflected their specific histories of deposition, diagenesis, and weathering. In brief, faulting established the structural grain that: (1) controlled cavern development during post-Miocene time, (2) established the topographic breaks that localized rapid stream incision and (3) provided gross lateral boundaries for the aquifer host rock in the eastern river basins.

There are several processes which acted on this structurally prepared ground. Mechanical and chemical erosion by surface streams occurred in response to a change in base level. Erosion, however, did not occur equally in all areas. The diversion of large volumes of surface flow in eastern basins by stream piracy locally enhanced capabilities for surface erosional processes. Downwasting in the eastern basins also was abetted by higher rainfall rates. Because of increased downcutting, low topographic levels were reached that intersected the aquifer and allowed a few loci for discharge of groundwater to become established. Near the intersection of the Balcones escarpment with the major drainage courses, the surface flow is augmented by spring discharge. Meantime, in areas such as the Nueces basin, surface flow and erosion were diminished by infiltration. Ultimately, both recharge and spring discharge were increased by localized dissolution of limestone because of continued exposure of soluble rock to through-flowing waters.

SURFACE-DRAINAGE RESPONSE TO BALCONES FAULTING

The generalized, mainly geometrical, region-wide evidence for stream piracy (Fig. 3) shows how the determinants for aquifer development can be tied to surface erosional processes. These presumed piracy events are ancient, perhaps as old as early Miocene. No clear-cut response is expected in present stream regimens or deposits, nor is any such response observed. Any evidence for ancient piracy events would be expected to occur only on the drainage divides and not in valley bottoms or in present stream regimens. Yet fluvial deposits on drainage divides underlain by resistant bedrock in a highly dissected terrain are highly susceptible to the effacing actions of erosion.

There are alluvial deposits at various levels across the inner Gulf Coastal Plain where substrate consists of easily erodible clay and marl strata (Barnes 1974a, b, c). But these gravel deposits occur in the western as well as in the eastern river basins, so that these gravel deposits on the Coastal Plain do not substantiate the piracy hypothesis. The geometry and topographic position of these deposits can, however, augment the geometrical stream-net and drainage-net picture already proposed. This is done by extrapolating depositional trends on the Coastal Plain "up gradient" to relict fluvial features on drainage divides as demonstrated by Woodruff (1977).

The Hill Country is a carbonate-rock terrane in which fluvial deposition is restricted in areal extent. This is an area in which alluvial materials are much more easily eroded than underlying limestone bedrock. For these reasons, no inverted topography exists such as that along the Coastal Plain. Nonetheless, scattered fluvial features do occur on uplands in the Hill Country, and notably, these features occur on drainage divides near some of the abrupt elbow turns in present streams. They exist in the exact areas the piracy hypothesis and regional geometrical features predict they would occur.

Preservation of fluvial features is associated spatially with upland karstic plains. This is probably because the karstic plains have afforded avenues for subsurface infiltration of water rather than the channelling of this incident precipitation into surface drainage courses with concomitant erosion. Because of gentle slopes, resistant bedrock, and predominant subsurface infiltration of water on these karstic plains, the drainage density is low (Woodruff, 1975, p.25). Thus, karstic plains are an ideal locality for the preservation of relict landforms.

Karstic plains also occur along lowlands adjacent to active streams where stream discharge is attenuated and recharge occurs via the "recharge caverns" of Thrailkill (1968). Recharge caverns occur along some low-lying reaches of Cibolo Creek, Medina River, and in similar local terranes within the Nueces River basin (Fig. 5c). In each of these areas, the substrate is resistant limestone. The caverns afford direct avenues for groundwater recharge and surface stream activity is correspondingly lessened. The "equilibrium landscape" of Hack (1965) occurs where the landforms are adjusted to the ongoing processes. The probable equilibrium landscape for resistant, solution-prone limestones is the low relief karstic plain. The topography, soils and other characteristics of these terranes are determined by the processes of concentrated groundwater infiltration coupled with attenuated erosional or depositional activity by surface streams. Thus, a low-relief carbonate-rock terrane coexisting with fluvial features at topographic levels far above active stream courses may be out of adjustment with present landforms and processes. It is deduced that the landform-substrate assemblage on upland karstic plains represents a former level of slow fluvial downcutting with high rates of groundwater recharge that resulted in the development of an extensive cavern network.

The disequilibrium between topographically high, relict karstic plains and adjacent deeply incised areas is significant in both a geomorphic and a hydrogeologic context. Geomorphically, the disequilibrated association is in itself an indicator of piracy in the eastern basins, as no such high relict karstic plains exist near the fault zone in the western basins. For example, Guadalupe River has an enormous erosional impetus because of basin size and subhumid climatic conditions. In terms of downcutting, this river has acted as would be expected from its erosional capabilities; it is deeply incised. However, the presence of relict upland plains in the river's mid-basin is all the more perplexing. That is, if any stream in the region should have a throughly dissected basin, with maximum hillslopes and minimum hilltops, it should be Guadalupe River. That the most dissected basins occur within the Nueces system, and extensive remnant highlands occur in the Guadalupe watershed, means that there must have been either drastic changes in underlying bedrock or differences in prior drainage history. Bedrock is the same regionwide, but stream piracy affords a means for explaining this observed condition (Woodruff and Abbott, 1979).

The hydrogeologic significance of these disequilibrated landscapes relates to inferred changes in locations and magnitudes of the recharge-discharge couplets. Before piracy occurred, high rates of recharge probably occurred in the eastern as well as the western basins, as evidenced by karstic plains on the eastern divides. Although the locus of discharge of these waters can only be inferred, an eastern river such as the Guadalupe would have had a somewhat lessened discharge and lower erosion rate owing to water losses into the cavernous aquifer. Only after integration by the Guadalupe of its present headwaters and subsequent breaching of the karstic recharge plain would marked increases in downcutting have occurred. Because then the Guadalupe River was draining the cavernous aquifer system that it had previously recharged.

Piracy-induced incision plus high surface discharge from a large subhumid river basin combined to produce the highest erosion rates of the entire region. This ultimately accomplished two things: 1) erosion provided topographically low points for spring discharge that became engrained as base levels toward which most of the artesian aquifer flowed. And 2) in the Guadalupe River basin, incision occurred at such a high rate that most of the upper aquifer levels were completely breached, and discharge from the aquifer (instead of recharge into it) became the major process. Part of the aquifer system draining to San Marcos Springs apparently does extend beneath Guadalupe River, and the Edwards Limestone crops out along a short reach of this deeply-incised river. Yet no long-term recharge is shown to have occurred for Guadalupe River (Table 1). This anomaly may be explained by the relatively small volume of caverns within the part of the aquifer that underlies Guadalupe River. Thus, the pore space beneath Guadalupe River may be essentially full of water under normal climatic conditions, and only during extreme drought conditions might this cavern system be able to accept recharge from Guadalupe River. This thesis is substantiated to some extent by the lesser fluctuations of discharge from San Marcos Springs during times of drought compared to the normally larger Comal Springs (Brune, 1975). Not only is Comal Springs probably more adversely affected by increased discharge by well-pumpage in the San Antonio area, but San Marcos Springs may be recharged to some extent during very dry years by Guadalupe River--a condition that does not occur during wetter times simply because the cavernous pore space within the small segment of the aquifer that underlies Guadalupe River is normally filled to capacity.

Where Guadalupe River crosses the Balcones fault zone, its drainage area increases by 15 percent while its mean annual discharge increases by 34 percent (U.S. Geological Survey records--courtesy of Texas Natural Resources Information System). This increased rate of flow across the fault zone is a result of higher rainfall in the middle part of the basin, input of water from Hueco Springs, and presumably little or no recharge into the Edwards aquifer. During the peak drought year of 1956, however, discharge increased across the fault zone by only 12 percent--a decrease in expected flow of about 84 hm^3. This is a 36 percent decline compared to long-term yearly averages. Assuming that the drought's effects on the water budget had equal impact throughout the river basin, there are only two means for effecting this relative decrease in discharge: diminished flow from Hueco Springs or infiltration into the Edwards aquifer. Hueco Springs did indeed experience decreased flow; no spring discharge was recorded during 1956 (Texas Board of Water Engineers, 1959). But in order to attribute all of the decreased Guadalupe River discharge through these reaches to diminished spring discharge would require a decline of 2690 l/s in the long-term rate of flow from Hueco Springs. There is no exact figure for mean annual discharge from Hueco Springs because of their erratic flow. However, Brune (1975, p. 38) cited 3710 l/s as the maximum discharge for Hueco Springs. He further listed 33 spring-discharge rates measured over a period of 48 years, the highest of which was 2322 l/s while the lowest was zero. Moreover, all 136 discharge measurements for Hueco Springs cited by the Texas Board of Water Engineers (1959) present values less than the average rate required to account for the computed water loss from Guadalupe River. It is likely that some fraction of the diminished flow in Guadalupe River during drought periods is a result of recharge into the Edwards aquifer.

INTEGRATION OF LANDFORM EVOLUTION AND DEVELOPMENT OF THE EDWARDS AQUIFER

Determinants that shaped the present recharge-discharge geometry of the Edwards aquifer began during Early Cretaceous time with differential uplift across the San Marcos platform and associated early development of cavernous porosity in the Edwards Limestone in the area that later was to become part of the San Antonio and Guadalupe River basins. Subsequent burial by younger Cretaceous rocks of low permeability precluded further significant porosity development during Cretaceous time. During Miocene time, Balcones faulting created a network of fractures that criss-crossed the Edwards Limestone along a strike distance of 545 km. These fractures not only provided gross structural boundaries for much of the 400 km long aquifer, but also they superimposed additional permeability conduits upon both primary (interparticle and other) and secondary (Cretaceous dissolution) porosity systems. Fault displacement was greatest in the very areas along the San Marcos platform that had experienced Cretaceous augmentation of primary porosity. Lesser fault displacements occurred in the areas southwest of the San Marcos platform. This affected aquifer development in three ways.

1. The western part of the fault system was dropped "down-to-the-coast" the least and thus became the structurally highest part of the Edwards Limestone. This was later reflected in a higher topographic level for Edwards outcrops in southwestern areas--especially in the Nueces watershed.

2. The greater fault displacements in the east caused the Edwards Limestone to be bounded structurally by rocks of lesser permeability and solubility. The compartmentalization into discrete lithic packages channeled groundwater flow and thus concentrated porosity enhancement within major fault blocks (Abbott, 1975).

3. The geometry of faulting set in motion the aforementioned surface drainage responses (Fig. 5). Stream piracy resulted from the geometrical relations between pre-faulting surface drainage nets in the western and eastern basins and the strike of the fault zone. Greater fault displacement in the eastern areas resulted in more rapid incision by streams flowing normal to the incipient escarpment. These rapidly eroding streams were the first to exhume the already porous Edwards Limestone. This exhumation might have occurred initially before headward stream reaches captured major regional streams. But at any rate, piracy and the resulting vigorous downcutting provided exposures within the Edwards Limestone at low topographic levels.

As soon as the Edwards Limestone was breached by the pirate streams, pent-up groundwater was released from the proto-aquifer, thus beginning the engrainment of the flowpaths of groundwater moving toward these few discharge points (see Figs. 2c, 2d). Notwithstanding the presence of primary porosity, Cretaceous solution-enlarged porosity, and Miocene fracture porosity, an effective groundwater flow system could not have developed until the overlying blanket of fine-grained sedimentary rocks was breached, thus exposing the soluble limestone to both recharge and discharge. Continual region-wide groundwater circulation developed as component streams of the Nueces system exhumed the

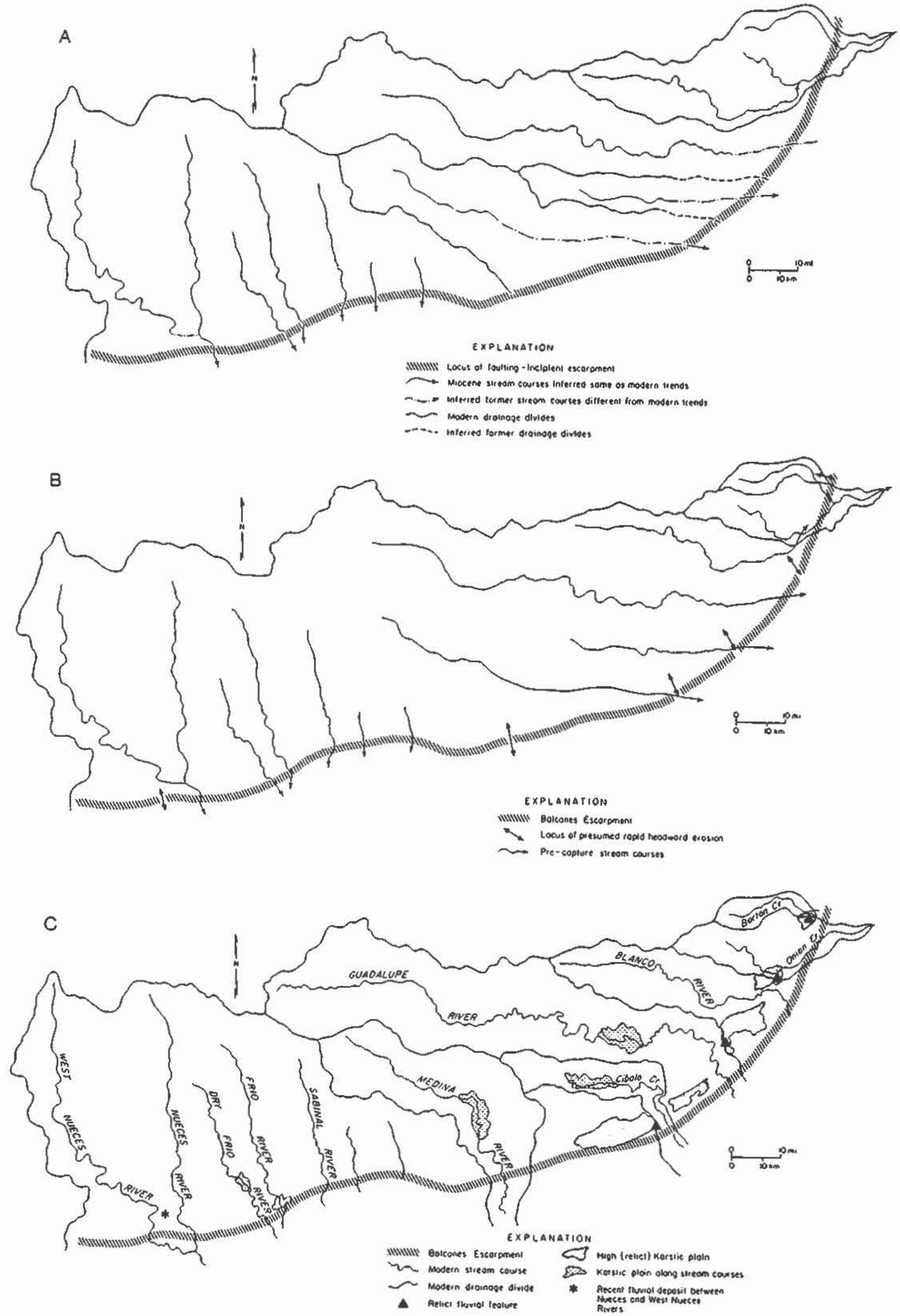

Figure 5. Drainage-basin evolution within the central and Barton Springs segments of the Edwards Aquifer:

A. Pre-piracy drainage configuration;
B. Scarp-normal pirate streams;
C. Modern drainage configuration (modified from Woodruff and Abbott, 1979).

structurally and topographically higher Edwards Limestone in the western basins. Downcutting was less rapid there because of lesser fault displacement and because there was no piracy-initiated increase in discharge. Ultimately, because of lower rates of downcutting by western streams coupled with lesser fault-displacement, these western basins were thoroughly dissected. This resulted in broad expanses of limestone being exposed along stream courses at relatively high topographic elevations.

Interconnection among the drainage catchment areas by fault-generated fracture systems allowed long-distance interbasin groundwater transfer from the topographically higher western areas to the lower, more permeable discharge points to the northeast. This set in motion the continuously circulating, self-ramifying groundwater flow system that converged toward the loci of the few springs. In this way, the initial discharge sites became the "drains" for the central segment of the aquifer, drawing on waters throughout the several drainage basins that encompass more than 17,695 km^2. In the same way, Barton Springs became the drain for the underground watershed comprising the surface catchment areas of Barton, Williamson, Slaughter, Bear, Little Bear, and Onion Creeks.

The ancient engrainment of the aquifer helps explain noteworthy features of the present Edwards aquifer system such as the paucity of springs and the origin of the "bad-water line." Although the Edwards aquifer in the fault zone is about 400 km long, there are only about a dozen large springs discharging from the system (Sayre and Bennett, 1942). Six of the major springs occur in the 280 km-long central segment: Leona Springs in Uvalde County; none in Medina County; San Antonio and San Pedro Springs (four km apart and rising along the same fault) in Bexar County; Comal and Hueco Springs in Comal County; and San Marcos Springs in Hays County (Fig. 4). These springs issue forth at progressively lower elevations to the northeast, and all but Leona Springs occur near major pirate streams. They probably discharge from enlarged lower-level conduits of the initial flow systems honed to the earliest discharge sites. That is, the loci of discharge probably migrated to progressively lower topographic levels near fault traces as dictated by changing base levels. The controlling base levels were in turn established by vigorously downcutting pirate streams. The general lowering of interfluvial areas and exposure of the Edwards Limestone over large areas have not caused more springs because the plumbing system was engrained long ago toward the few original discharge sites.

The southeastern boundary of the aquifer is a "bad-water line" that separates the potable water of the cavernous, high-yield aquifer from the high salinity water on the downdip side. Although the bad-water line is roughly parallel to the trend of the Balcones fault zone, its detailed course generallly disregards individual faults and facies boundaries (Abbott, 1975; Woodruff and others, 1982). It can be understood as the solution-engrained original flow boundary of groundwater that moved toward the earliest discharge sites. This hydraulically-controlled boundary probably marks the down-dip potentiometric boundary as originally affected by the subtle draws of low elevation springs.

Initially, recharge probably occurred through karstic plains at high topographic levels within the San Antonio and Guadalupe watersheds (Fig. 5c), and much of the cavern development was confined to individual fault blocks in a trend subparallel to the modern system that lies beneath the western edge of the Gulf Coastal Plain. When streams trending normal to the fault scarp effected piracy, the greater volumes of flow rapidly cut through the high-level karstic plains and stranded some of the subjacent cavern systems that formerly recharged their local areas. Upland karstic plains are the relicts of this former equilibrated landform/process couplet. The post-piracy couplet enhanced while the development of caverns at lower topographic levels, as is presently seen along Cibolo Creek and Medina River (compare Figs. 2d and 5c). These low-lying karst plains provide a periodic influx of recharge undersaturated with respect to calcite and dolomite which is so important for the continued solutional growth of the Edwards aquifer.

The recharge-discharge geometry described here does not fit the general concept which holds that dissolution is concentrated near recharge sites where groundwater is least saturated with respect to calcite and dolomite and thus is most aggressively able to form caverns. If this common view of cavern formation held for the Edwards artesian aquifer, then the cavern systems in Kinney, Uvalde, and Medina Counties should be more highly developed, and yields from springs and wells should be greater there. Likewise, cavern development in Bexar, Comal, and Hays Counties should be much less than it is, because groundwater that has traveled a long distance should be saturated or supersaturated with respect to calcite and dolomite and hence unable to accomplish any further dissolution. If the groundwater had been mostly saturated during the developmental history of the aquifer, then caverns in the eastern areas would be poorly developed, and yields from wells and springs would be low. Since the caverns are best developed near the distal end of the groundwater system, then clearly the groundwater passing through Bexar, Comal, and Hays Counties has primarily been undersaturated with respect to calcite and dolomite.

Today groundwater within the Edwards aquifer is at least seasonally undersaturated, as shown by negative saturation indices calculated for calcite and dolomite from well and spring water samples near Comal, San Marcos, and Hueco Springs by Pearson and Rettman (1976) and by Abbott (1977a). The mechanism that maintains at least seasonal undersaturation in the ground- water appears to be the mixing-of-waters effect explained by Thrailkill (1968). Introduction of recharge, even if it is saturated or supersaturated, may cause undersaturation in the main groundwater body if the recharge is cooled upon entering or if it is mixed with water in equilibrium with a lower partial pressure of carbon dioxide. The necessary process is the addition of carbon dioxide into the main groundwater body. The resulting increase in carbonic acid permits further dissolution of limestone and dolomite. Maintenance of chemical undersaturation over the long distances within the confined Edwards aquifer must be a result of the introduction of high-volume vadose flows recharged through sinks in stream bottoms in Bexar and Comal Counties. Although the recharge supplied by Cibolo, Dry Comal, and other creeks crossing the middle part of the aquifer composes less than one-third of the water in the aquifer, its delivery occurs at strategic points that promotes undersaturation. Moreover, because rainfall in the region commonly occurs as downpours from convective thunderheads, much of the recharge occurs rapidly and is undersaturated with respect to calcite and dolomite.

SUMMARY AND CONCLUSIONS

The primary determinants that caused streams in the eastern part of the Balcones escarpment to incise deeply to a topographically low level were the greater fault displacements across the area of the Cretaceous San Marcos platform compared to areas to the southwest. Faulting markedly affected surface and subsurface drainage evolution in several ways:

1. Progressive downdrop of fault blocks toward the Gulf of Mexico created a disequilibrium along established surface streams graded to their previous base levels.

2. Resistant limestone strata juxtaposed against more erosive rock resulted in additional changes in stream regimes, and the locus of major fault displacement was perpetuated as a fault-line scarp.

3. Fractures associated with faulting offered preferred orientation for surface stream erosion into resistant bedrock. Additionally, fractures acted as initial conduits for recharge and regional transfer of groundwater. These underground flow conduits and the pre-existing porosity within the Edwards Limestone were selectively enlarged by dissolution.

4. Several lines of evidence, including the frequency of caves and the occurrence of cave fauna, indicate that cavernous porosity is well developed and interconnected. The arcuate path of the Balcones faults runs 240 km in a least-distance path from the western drainage divide in Kinney County to San Marcos Springs; some groundwater travels at least this far.

Streams in the eastern part of the region originally trended at acute angles to the strike of major fault displacement. Thus, when escarpments began to form, the eastward-trending streams were vulnerable to piracy by rapidly eroding, smaller streams with courses normal to the escarpment. After piracy, more rapid incision commenced because of the much larger discharge suddenly available from newly acquired headwaters. No such situation existed in the more arid Nueces basin, where total fault displacement was less and streams already flowed normal to the escarpment. Thus, rather than incising deep valleys, the component streams of the Nueces system established generally wider valleys and more extensively dissected uplands at higher topographic elevations, despite the fact that these streams crossed the same rock types in which incision occurred elsewhere. As alluvial plains were created in the western basins, and as infiltration occurred, low-lying karstic plains were formed as described by Thrailkill (1968) for recharge areas.

The impetus for the transfer of groundwater from the semiarid western region to the subhumid northeastern region resulted from several factors:

1. The porosity and permeability owing to faults and fractures associated with the Balcones fault system provided avenues for meteoric water to enter the Edwards Limestone, and the fault-block trends guided or channeled the movement of water.

2. Although the regional dip is to the southeast, a major component of dip within the Balcones fault zone is toward the northeast.

3. The overlying seal of low permeability sedimentary rocks was breached by rapidly degrading, scarp-normal pirate streams in the eastern watersheds. When these pirate streams intercepted the Edwards Limestone they created discharge sites for the pent-up groundwater.

4. The creation of a few discharge sites in the east and the broader dissection in the west set in motion a continously circulating groundwater flow system that converged toward the few springs. These springs are most voluminous in areas containing cavernous porosity developed during the Cretaceous on the San Marcos platform.

The transmitted effect of a few discharge sites at the low-elevation end of the fault zone drew confined groundwater from more than 200 km away. The originally subtle draw of low-elevation springs was engrained into an integrated cavern system by the dissolution accomplished by groundwater kept undersaturated by periodic influxes of fresh water. The extensive development of caverns near the discharge sites emphasizes the influence of the progressively greater flow of groundwater funneled toward the springs. When the aquifer system is viewed in scale with its great extent, few springs, and small number of recharge streams it appears to be a long, thin tabular container with few entry and exit points.

The regional potentiometric gradient extends from northwest to southeast down the regional dip, yet most groundwater flows through cavern systems parallel to the Balcones faults which are at right angles to the apparent regional potentiometric gradient. In effect the Edwards Limestone is like a tabular container inclined to the southeast, but fluid flow is stopped at the downdip permeability barrier (container wall) expressed as the "bad-water line". The early discharge sites created by the pirate streams are analogous to pulling plugs from the northeastern edge of the southeast-inclined container. Water runs to these exit points rather than down the regional slope.

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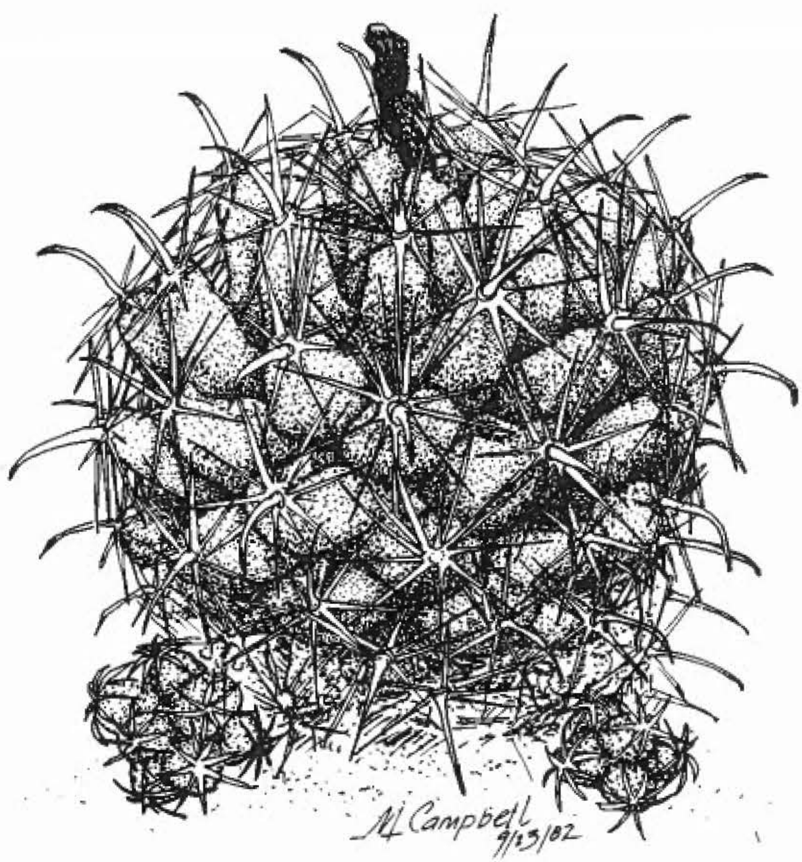

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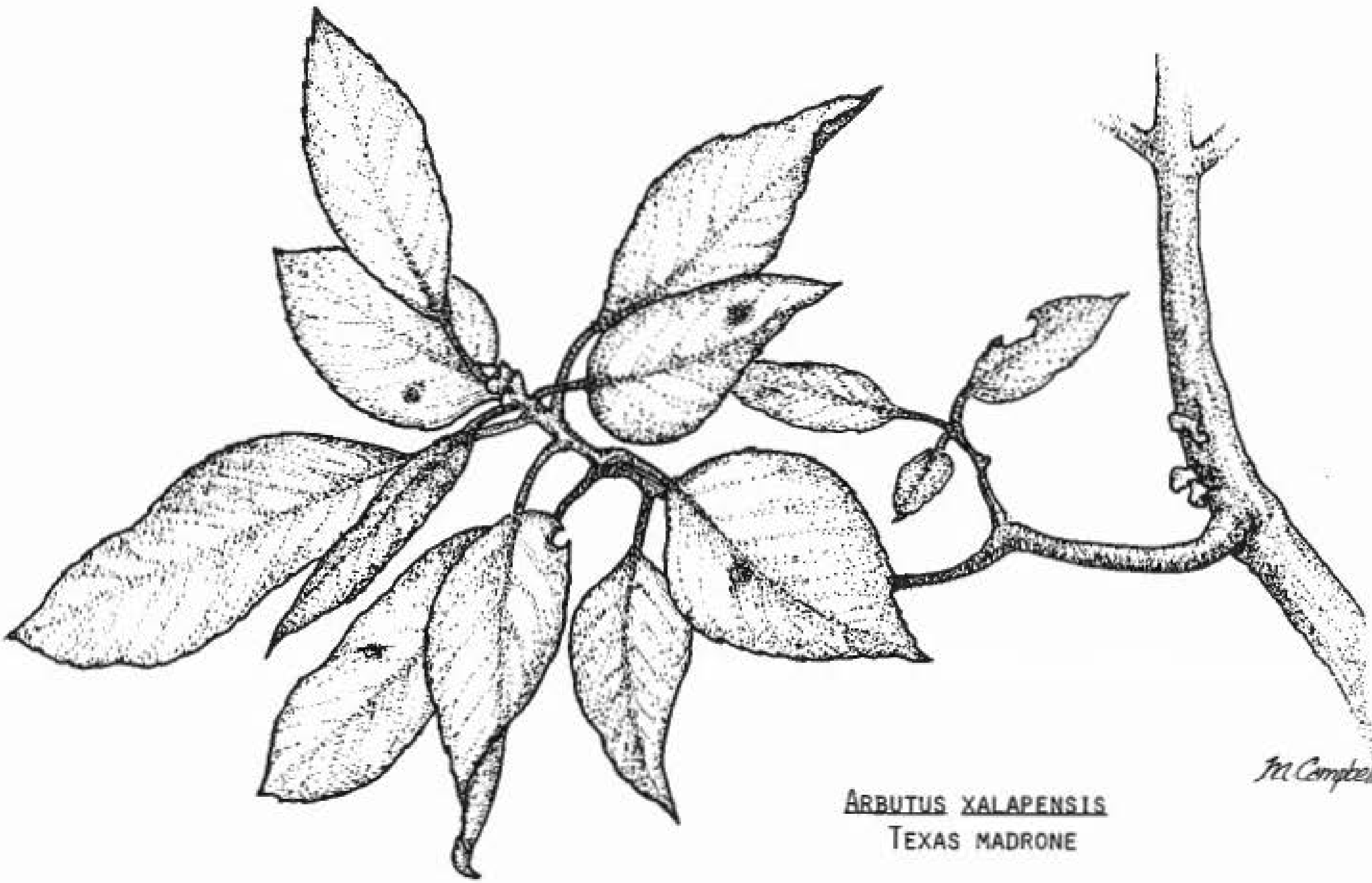

ARBUTUS XALAPENSIS
TEXAS MADRONE

CAVERN DEVELOPMENT IN THE NEW BRAUNFELS AREA, CENTRAL TEXAS

Ernst H. Kastning
Department of Geology
Radford University
Radford, Virginia 24142

ABSTRACT

Development of caves in the vicinity of Cibolo Creek near New Braunfels progressed in response to two distinct tectonic episodes. First, uplift of the San Marcos Arch subjected Lower Cretaceous rocks to subaerial exposure and heightened topographic relief that promoted deep circulation of groundwater through fractures produced during the tectonism. Primary porosity in the Glen Rose Formation became enhanced as cavities were solutionally enlarged; but openings remained poorly integrated. During the Late Cretaceous, the region was episodically covered by shallow seas which deposited calcareous, siliclastic, and marly sediments above the Glen Rose Formation. The second disturbance, Balcones faulting during the Miocene, heightened local relief in the immediate area and thus steepened hydraulic gradients. Groundwater moving along the gentle southeastern dip enlarged pre-existing, northwest-trending fractures as well as many of those produced by the faulting. As a result, major caves of the area, such as the Natural Bridge Caverns System, consist of well-integrated conduits of large cross-section that are angulate in plan-view and correspond to flowpaths favorably aligned along open fractures.

During the Quaternary streams draining the Edwards Plateau incised rapidly in the vicinity of the Balcones Escarpment. Levels of groundwater declined in response to cutting of valleys, and levels of passages in caves developed in a descending sequence. Passages were enlarged to canyon-like cross-section by subsequent vadose streams and later abandoned as water circulated at greater depths. Major collapse of ceilings in some places blocked active conduits and promoted development of routes of diversion, in places along upper levels.

In general, groundwater flowed to the southeast. Northwest-trending fractures account for a large percentage of the overall orientation of cave passages. However, many northeast-trending fractures and some fractures of conjugate sets provided cross-overs in the paths of flow among adjacent, master fractures and thereby account for a significant number of passages as well.

INTRODUCTION

Several large caves occur approximately 20 km west of New Braunfels in west-central Comal County, in an area bounded by Cibolo Creek and Bat Cave Fault (Figure 1). The origin of Natural Bridge Caverns and other nearby caves is intimately tied to the depositional, structural, and erosional evolution of the San Marcos Arch and Balcones Fault Zone. Karstic drainage and conduit development are strongly aligned along favorable lithostratigraphic horizons and zones of fracture. The caves exhibit phenomena indicative of episodes of marine deposition, tectonism, surficial downwasting, fluctuations in groundwater levels and flow rates, and speleothem deposition.

DESCRIPTION OF AREA

The cavern area is generally underlain by Lower and Upper Cretaceous rocks (George and others, 1952; Newcomb, 1971; Barnes, 1974). The lowest cavernous unit is the upper member of the Glen Rose Formation, a thin-bedded sequence of fine-grained dolomite and marl of variable hardness (Stricklin and others, 1971). Beds are alternatingly resistant and recessive and weather to form stairstep-topography. The uppermost beds are massive and dolomitic. Up to 17 m of the upper member of the Glen Rose are exposed along valleys of incised streams.

The Glen Rose is overlain by the Bull Creek Limestone and Bee Cave Marl Members of the Walnut Formation. The Bull Creek is a thin- to medium-bedded, hard, well-sorted biomicrite, intramicrite, and fossiliferous intrasparite, and the Bee Cave is a clayey, fossiliferous micrite and fossiliferous marl (Moore, 1961, 1964). The Walnut is approximately 14 m thick in this area.

The Kainer Formation of the Edwards Group overlies the Walnut and consists of aphanitic to coarse-grained, massive- to thin-bedded, hard, brittle, resistant limestone. It is locally dolomitic and bored, contains abundant chert, and in its basal part is nodular, honeycombed, and contains zones of solutional and collapsed breccia.

The cavern area overlies the faulted outcrop of the Edwards Group, bounded on the northwest by the Tom Creek Fault and on the southeast by the Comal Springs Fault (George and others, 1952; Kastning, 1978). The outcrop of the Edwards Group within the Balcones Fault Zone is 20 km wide in this vicinity, and recharge enters the unconfined zone of the Edwards Aquifer by direct infiltration. The bed of Cibolo Creek between Boerne and the western boundary of the outcrop of the Edwards is part of the zone of recharge for the Edwards Aquifer. Water is lost to the Glen Rose Formation along the bed of Cibolo Creek, and is transmitted into the Edwards Limestone across

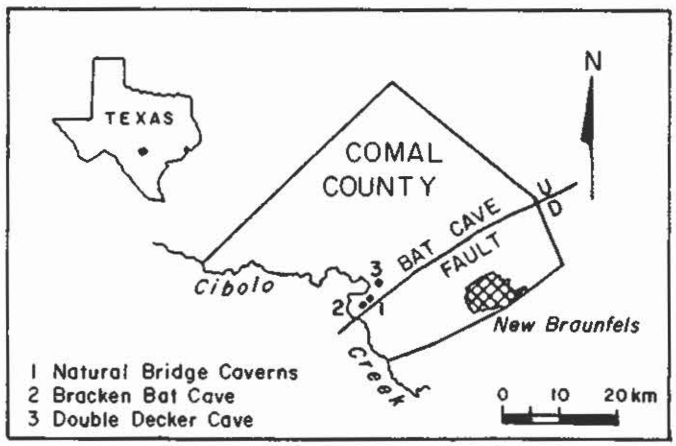

Figure 1. New Braunfels area, central Texas.

in Abbott, Patrick L. and Woodruff, C.M., Jr., eds., 1986, **The Balcones Escarpment, Central Texas**: Geological Society of America, p. 91-100

the Hidden Valley and Bear Creek Faults, where the Glen Rose and Edwards are in juxtaposition (George and others, 1952; Kastning, 1978). Comal Springs, within the New Braunfels city limits, is the largest exsurgence of groundwater from the Edwards Aquifer (Guyton and Associates, 1979).

The cavern area lies along the southwestern flank of the San Marcos Arch which was raised along its northwest-trending axis during the close of the Early Cretaceous (Rose, 1972; Woodruff and Abbott, 1979; Kastning, 1983). The deformation that produced the arch created several sets of fractures. Those of a northwestern orientation lie parallel to the axis of the arch and are accompanied by two sets of conjugate fractures. These sets resulted from extensional stresses during uplift. Later deformation during Balcones faulting produced another set of extensional fractures trending to the northeast and parallel to the individual faults (Kastning, 1981, 1984).

Subaerial exposure of Lower Cretaceous rocks brought about by uplift of the San Marcos Arch and incision of streams draining the Edwards Plateau in response to Balcones faulting during the Miocene were crucial in the evolution of circulation of karstic groundwater and development of caves. The chronology of these events and the influence of geologic structure on speleogenesis are described below.

DISTRIBUTION OF CAVES AND PREVIOUS INVESTIGATIONS

There are several large caves in this area, including the Natural Bridge Caverns System, Bracken Bat, Double Decker, Ebert, Dinosaur, Bear Creek, Beal Ranch, Rompel, Zuercher No. 1, and Brehmer Caves (White, 1948; Reddell, 1964a,b; Beck, 1968).

Knox (1975) inventoried points of recharge, including caves and enlarged fractures, in the upper basin of Cibolo Creek in Kendall, Comal and Bexar Counties. She correlated these with available hydrologic data for the basin.

Abbott (1973, 1975, 1977a,b) investigated the hydrogeology of the Edwards Aquifer in the vicinity of New Braunfels and attempted to relate development of caves to the diagenetic evolution of the Edwards Limestone and to the hydrochemistry of the aquifer. The results from this analysis were later incorporated with an interpretation of the evolution of the drainage-basin into a plausible hypothesis for the development of cavernous porosity in the area of the San Marcos Platform (Woodruff and Abbott, 1979).

Geologic studies undertaken in recent years in the Natural Bridge Caverns System have focused on the influence of lithology and structure on the development of the cave (Kastning, 1978, 1980, 1981, 1984; Knox, 1981). Renewed surveying of the cave by Orion Knox and others has produced one of the most detailed maps of a major Texas cave (Kastning, 1978, plate 2).

DEVELOPMENT OF CAVES

Description of Natural Bridge Caverns System

The Natural Bridge Caverns System, in the west-central part of the Bat Cave 7.5-minute U.S.G.S. Quadrangle, consists of three separate caves: the North Caverns, the South Caverns, and the Jaremy Room (Figure 2). These are remnants of a once larger cave now segmented by collapse and development of dolines. This is suggested by the orientations and horizontal and vertical alignments of passage segments. Most known passages are shown on the map, but several side-passages at the north end of the caverns remain to be surveyed. Total surveyed length of the system is presently 3354 m. The North Caverns, containing the commercially developed passages, is presently the eleventh longest cave in Texas. The end-to-end extent of Natural Bridge Caverns System is 1160 m. Detailed descriptions of the system, history of its exploration, and bibliography are given by Knox (1962) and Reddell (1964a,b).

Chambers of the Natural Bridge Caverns System are as large as any known from caves of the eastern Edwards Plateau. Speleothems within the cave are among the largest and most spectacular in Texas. They include massive stalagmites, soda-straw stalactites up to 4.3 m long and "fried-egg" stalagmites (Beck, 1978).

The only natural entrance to the system is in a large collapsed doline directly behind the present visitor-center. A natural span of limestone bridges the doline, providing the namesake for the cave. The doline, entrance, and side passages to the southwest have been known for some time.

Pluto's Anteroom was discovered in 1960, and all passages to the north were explored during the period 1960 to 1963. The North Caverns, from the entrance to the Hall of the Mountain Kings, was developed for tourism and opened to the public in 1964 (Heidemann, 1979). An artificial tunnel was excavated between the surface and the Hall of the Mountain Kings in order to provide an exit for tours. It has intersected a small, unnamed cave midway along its length.

The management of Natural Bridge Caverns suspected that a continuation of the large, main passage of the North Caverns might exist to the south, beyond the collapsed doline. This was confirmed by exploratory drilling in the late 1960's when five boreholes were driven to allow entry into the new chambers. One hole intersected the Jaremy Room and another pierced the South Caverns and a short, overlying passage. Views of the cave in plan and profile (Figure 2) clearly suggest that all segments of the system were once interconnected.

The plan-view of Natural Bridge Caverns shows that most passages consist of linear segments oriented along several preferred directions. An overall north-south trend persists, particularly for the passages of larger cross-section. Several east-trending side-passages join the main cave.

The profile clearly indicates that levels of passages have developed along several, favorable horizons. Vertical position of levels in the cave is correlative with stratigraphic position (Figure 3). The dip is subhorizontal (less than one half of a degree to the southeast) in this vicinity. Large segments of the master conduit on the lowest level are wholly within the Upper Glen Rose Formation, including the South Caverns, Purgatory Creek, Grendel's Canyon, and the Limbo and Lake Passages. Above this level is another significant horizon of passages which includes the South Fault Passage, Chapel Hall, Jan's Long Crawl, Emerald Lake Passage and some shorter segments between the Inferno Room and Dome Pit. This level is also within the Upper Glen Rose, but nearly at its contact with the overlying Bull Creek Limestone Member of the Walnut Formation.

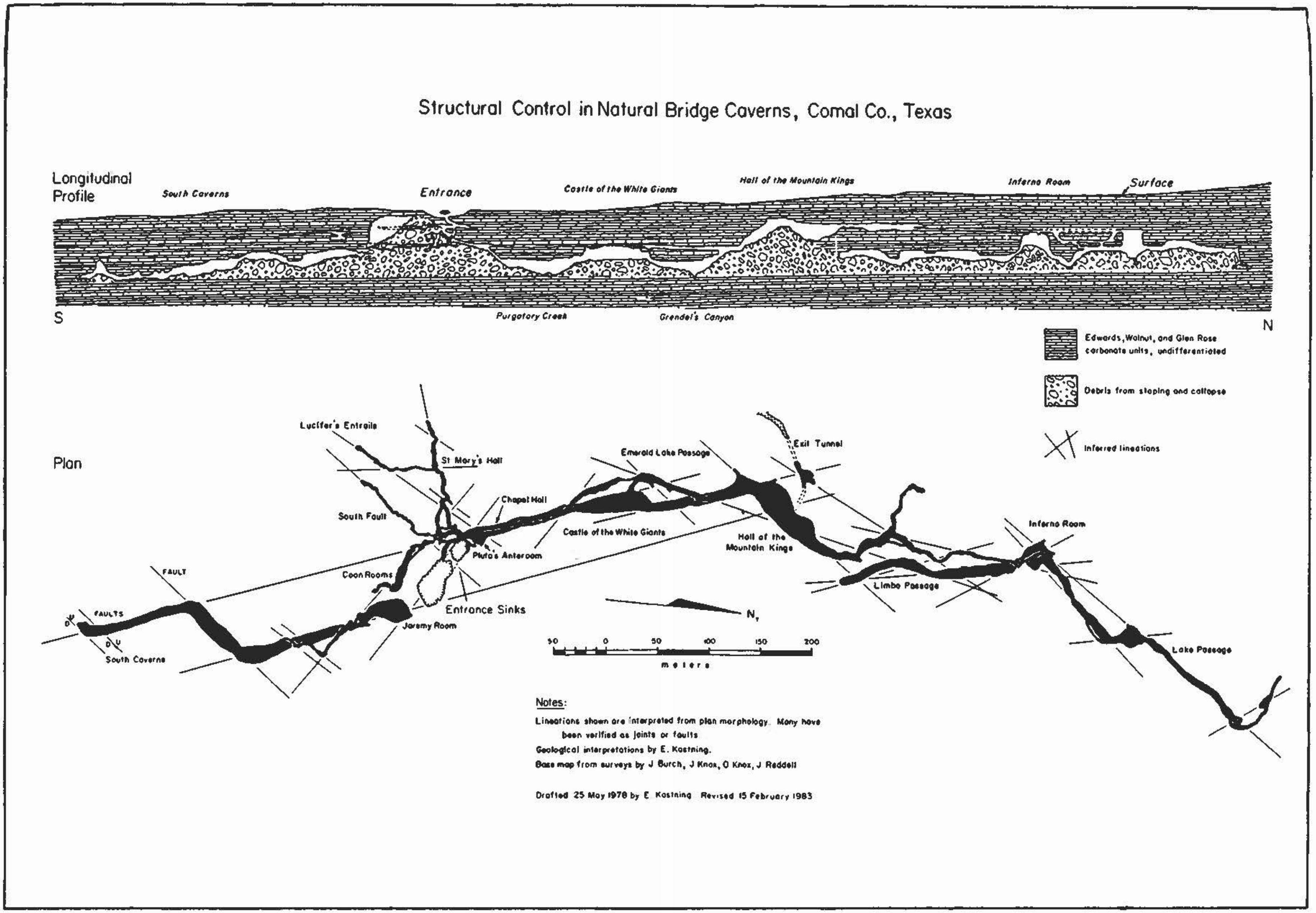

Figure 2. Natural Bridge Caverns. Profile shows horizons of cavern development and zones of collapse. Lineations indicated in plan view, many of which correspond to mapped fractures. From Kastning (1978, 1983).

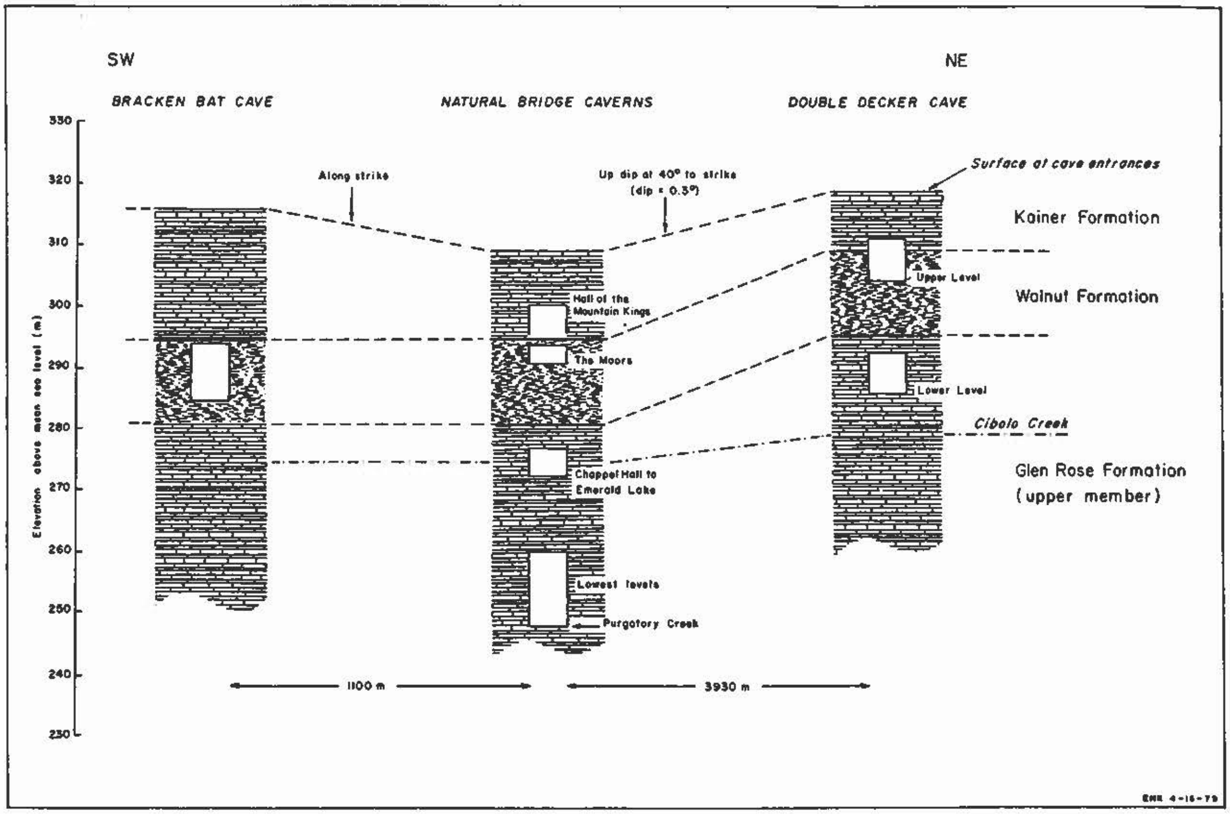

Figure 3. Correlation of horizons of passages within Natural Bridge Caverns System, Bracken Bat Cave, and Double Decker Cave. Topographic elevations at the entrances to the caves and at the nearest point on Cibolo Creek are indicated. From Kastning (1983).

Passages of shorter extent are found on two or more levels in the Walnut Formation. These are represented by (1) the isolated passage overlying the South Caverns, (2) St. Mary's Hall, (3) the Coon Rooms, and (4) the passage from the Moors to the Inferno Room and Dome Pit.

Natural Bridge Caverns presently contains two watercourses, both of very short extent within the cave. Purgatory Creek enters on the eastern wall of the main passage at one of the lowest points in the cave (64 m below the entrance). It curves once across the passage and leaves through the eastern wall only 18 m south of where it enters. These openings are alluviated and exploration is not possible. A second watercourse, River Styx, enters and leaves the northernmost section of the cave twice in its southward flow. River Styx may very well be an upstream segment of Purgatory Creek, but this remains to be confirmed by techniques of water-tracing. A well has been driven into the cave at River Styx from which water is pumped to the surface for use at the visitor-center.

Purgatory Creek is frequently dry, but during wet periods it increases in flow. Storms of high intensity cause sufficient flow in Purgatory Creek to inundate lower levels of the cave. A storm on May 11-12, 1972, caused devastating floods on the Guadalupe River and nearby Blieders and Dry Comal Creeks (Colwick and others, 1973; Baker, 1975, 1977). Three days after the storm, water in the cave rose approximately 18 m above the bed of Purgatory Creek. After the crest of the flood the level of water began dropping at about 20 cm per day (Knox, 1981). The floor of the Castle of the White Giants had been under approximately 2 m of water at this time. This is the largest flood recorded in the cave since its discovery.

Water enters the cave by infiltration even during long, dry periods. Seepage is sufficient to promote continual deposition of speleothems in most passages. The Chandelier formation, a large drapery-stalactite in the Castle of the White Giants, normally receives enough flow to allow water to fall from it in a continuous trickle rather than in drops. Moisture and humidity are noticeably high throughout the cave. Glass doors have been installed in the entrance and exit tunnels to maintain moisture levels and sustain the growth of speleothems.

Other Caves

Bracken Bat Cave is 960 m to the southwest of Natural Bridge Caverns (Figure 1). The entrance is in a doline 30 m in diameter and 10 m deep. The cave extends N 18° W for 130 m as a single large passage, averaging 20 m in width and 10 m in height. Severed by collapse of the doline at the entrance, the cave may extend to the northwest, but to date no such passage has been discovered.

Bracken Bat Cave has developed on one level. Stratigraphically, the main passage is in the Walnut Formation, just below its contact with the Kainer Formation of the Edwards Group (Figure 3). The slope of the entrance passes through the lower part of the

Kainer Formation. Bat Cave Fault, named after the cave, is approximately 200 m to the southeast.

Double Decker Cave is 3.93 km north-northeast of Natural Bridge Caverns in the northwest part of the Bat Cave Quadrangle (Figure 1). The cave has 208 m of surveyed passage and attains a maximum depth of 31.7 m below the entrance. The cave has developed on two levels and along two major directions. The Upper Level extends due east for 60 m from the entrance, and the Lower Level extends N 30° W for 45 m from the entrance before turning to the southwest for 20 m. Although Double Decker Cave is relatively short, its passages have large cross-sections. The pit at the entrance is in the Kainer Formation, the Upper Level has developed primarily in the Walnut Formation, and the Lower Level is wholly within the Glen Rose Formation (Figure 3). Floors of passages are generally covered by mud, breakdown, or flowstone.

Speleogenesis

Many caves of the New Braunfels area, including some of the largest ones, have developed in the upper member of the Glen Rose Formation despite a much greater areal exposure of the Edwards Group than that of the Glen Rose. Dissolution and speleogenesis have occurred within the alternating sequence of calcareous, marly, and dolomitic beds of the Glen Rose, but relatively little development has taken place in the overlying, crystalline, Edwards Limestone. Beck (1968) suggested that the caves had developed preferentially within calcareous beds in the Glen Rose and that large caves, such as the Natural Bridge Caverns System and Bracken Bat Cave have developed parallel to the high-velocity flow of groundwater caused by a convergence of flowpaths in the vicinity of these caves. Features mapped and interpreted by Kastning (1983), and recent hypotheses on the evolution of the cavernous Edwards Aquifer, suggest a new explanation for the origin of the Natural Bridge Caverns System and nearby caves, as described below.

Lithologic Control

The concordance of passages with stratigraphic horizons in the Natural Bridge Caverns System, Bracken Bat Cave, and Double Decker Cave has been well documented and suggests strong lithologic control (Kastning, 1978, 1983; Knox, 1981). Correlation of stratigraphic horizons within which major passages of the caves have developed is shown in Figure 3. Extensive passages of Bracken Bat Cave, the Natural Bridge Caverns System, and Double Decker Cave have developed in the Walnut Formation. In Natural Bridge Caverns and Double Decker Cave passages in the Walnut extend upward in places into the basal beds of the Edwards Limestone. This is the result of collapse of ceilings and upward stoping of passages (see below). These two caves also have large passages developed within the upper member of the Glen Rose Formation. The largest of the passages in the New Braunfels area is the one forming the lowest levels of the Natural Bridge Caverns System along its entire extent. It lies in the interval from 21 to 33 m below the contact between the Walnut and Glen Rose Formations (Figure 3).

Development of large passages in the Glen Rose and Walnut Formations may be attributed to enhancement of porosity following Early Cretaceous deposition, when the San Marcos Arch was elevated, and more than 30 m of the uppermost beds of the Edwards Group were removed by subaerial erosion (Rose, 1972). The accompanying increase in circulation of meteoric groundwater within the lower Edwards Group and underlying Walnut and Glen Rose Formation enlarged available pores.

Evidence for development of cavernous porosity predating development of integrated caves can be seen in Natural Bridge Caverns. Cavities in the upper member of the Glen Rose were enlarged during the early stages of circulation of groundwater and were subsequently filled with calcareous clay and marl. Laminations are easily seen in these deposits. Vugs lined with crystals of calcite occur in the Walnut Formation.

Some beds of the upper member of the Glen Rose Formation are highly porous in comparison with others above and below and are readily seen in walls of passages on most levels of the caves. Much of this porosity has resulted from leaching of burrows, and by dissolution of evaporites and fossils (moldic porosity). Undoubtedly circulation of groundwater during the mid-Cretaceous enhanced much of this porosity, but most enlarged cavities were presumably small and poorly integrated in comparison to those that developed later.

The greatest effect of enhanced porosity from the mid-Cretaceous occurred during development of caves following uplift of the Edwards Plateau, Balcones faulting, and regional dissection. Groundwater was transmitted to porous zones through joints created by the faulting and along favorable bedding-plane partings. Zones of primary and enhanced porosity were subsequently integrated into a network of conduits. As a result, passages of caves of this area typically occupy stratigraphic horizons that originally had a high effective porosity.

Some stratigraphic control has also resulted from the mineralogic content of the host-rocks. Dolomitic beds are generally poor formers of caves in the presence of strata of greater calcitic content (Rauch and White, 1970; Kastning, 1975). This is true of the caves of the New Braunfels area, where passages commonly occupy calcareous beds rather than dolomitic beds (Beck, 1968). However, the massive, dolomitic unit comprising the uppermost member of the Glen Rose does contain some passages. Moreover, selectivity of calcareous beds over dolomitic beds is present only among strata of uniform porosity and permeability because these have been the dominant, lithologic determinants for the vertical positioning of passages.

Structural Control

Each of the three caves studied in detail exhibit linearity in plan- and profile-view, suggesting strong, structural control (Figure 2). Detailed mapping of the caves and their geologic structure has shown that fractures such as bedding-plane partings, joints, and faults have guided the orientation and morphology of passages.

Bedding-Plane Partings

A few small passages have developed along bedding-plane partings with relatively little control by joints. Examples include meandering segments of the upper two levels in Natural Bridge Caverns. The widths of these passages commonly exceed their height, and some are characterized by anastomosing crawlways averaging 0.3 to 0.4 m in height.

Horizontal permeability along bedding-plane partings is evident in the caves where movement of groundwater can be observed. Purgatory Creek and River Styx in Natural Bridge Caverns occupy phreatic tubes oriented along such partings, and some speleothems have formed where seepage enters the cave along partings. Some seepage entering along the walls of the cave does so along the top surfaces of shaly beds where water has been perched.

Joints

Joints have exerted the greatest structural control on the morphology of passages. Joints are readily identified in ceilings of passages in all three caves. Most linear segments of passages in the Natural Bridge Caverns System have been verified as joints (Figure 2).

Joints measured in the Natural Bridge Caverns System have two major trends: N 20°-30° W and N 40°-50° E (Figure 2). The north-eastern joint-set is parallel to the Bat Cave Fault (Figure 1) and is a product of Balcones faulting. The northwestern set is not compatible with tensional stresses operating during normal (step) faulting. However, the strike of this set is nearly parallel to the axis of the San Marcos Arch, and joints of this orientation appear to be related to uplift along the San Marcos Platform during the Cretaceous. The northwestern joint-set accounts for 35 percent of the total length of passages in the Natural Bridge Caverns System, whereas the northeastern set represents 15 percent of this length. The remaining 50 percent of the length has been controlled by shorter joints of other orientations, by faults, or by bedding-plane partings.

Trends of most joints observed in Bracken Bat Cave lie in the intervals N 10°-30° W and N 0°-10° E. Joints of the former set trend parallel to the primary northwestern joint-set of the Natural Bridge Caverns System. Joints of the northeastern set, although present, account for little length of passages in this cave. The lower level of Double Decker Cave is mostly oriented along the dominant, northwestern set of joints. The upper level, however, is oriented along joints trending between N 80° E and S 70° E. The trend of this set is subparallel to the Zuercher Ranch Fault (strike of N 85° E) located just 275 m north of the cave.

Control by Faults

High-angle faults occur in the South Caverns of the Natural Bridge Caverns System and in Double Decker Cave. Faults in the Natural Bridge Caverns System are parallel to the Bat Cave Fault, and their throws generally measure less than a meter. A single fault in Double Decker Cave strikes parallel to the Zuercher Ranch Fault, and its throw is approximately 0.5 m.

Faults can enhance or inhibit the circulation of groundwater in carbonate aquifers, depending on (1) the type of faulting: normal versus thrust, (2) the type of stresses operating during faulting: tensional versus compressional, (3) the lithologies in juxtaposition across faulted strata, (4) the density of joints related to faults, and (5) the degree of brecciation or shatter and the thickness of such a zone (Kastning, 1977). Faults may also be of neutral influence. Thus, no general statement on the influence of faults on the flow of groundwater or on speleogenesis is universally valid. Oddly enough, examples of positive, neutral, <u>and</u> negative effects of faults on development of passages occur in the Natural Bridge Caverns System and Double Decker Cave. The southernmost 200 m of the South Caverns alone has been affected in each of these ways (Figure 4).

Box Canyon in the South Caverns has developed along a normal fault with a throw of 0.6 m. The fault is clearly visible in the wall at the southwestern end of this segment of passage where the cave turns to the southeast. Joints of narrow spacing, visible in the ceiling of the Box Canyon, suggest that tensional stress during faulting created a zone of enhanced permeability which became integrated with joints of the prominent northwestern set. The master conduit then developed along this integrated flowpath. The fact that the width of Box Canyon is greater than that of other segments of passages connecting with it may be explained by the high density of joints associated with this fault.

In the Fault Room to the south two visible faults transect the cave, but have no expression in the morphology of the passage (Figure 4). Apparently the small number of associated joints precluded enhancement of permeability, yet the movement of groundwater across the fault remained uninterrupted because displacements were small (0.3 to 0.6 m) and lithologies on both sides of the faults remained similar.

The main conduit of the Natural Bridge Caverns System ends abruptly at the southern terminus of the South Caverns. This termination is coincident with the Bat Cave Fault which has a throw of approximately 70 m in this vicinity (Figure 4). Here beds of the Kainer Formation are in juxtaposition with the upper member of the Glen Rose Formation. The lithologic change across the fault prevented the flow of groundwater across it and to the south. Presumably flow at this location became diverted to the northeast, in conjunction with the regional movement of groundwater to points of discharge at major springs along the Balcones Escarpment. The Bat Cave Fault is the southeastern boundary of the compartment in which groundwater of the area of the Natural Bridge Caverns System moves. There is no visible conduit leading from the Fault Room, apparently because it lies below the floor of breakdown and sediment.

Flowstone is being deposited where the fault transects Double Decker Cave at the drop between the Upper and Lower Levels. Here water from the surface infiltrates into the bedrock along the fault-plane and enters the cave as seepage.

Correlation of Caves with Surficial Fractures

Fractures were mapped from remotely sensed imagery of the New Braunfels area in order to ascertain how well joints and faults can be interpreted from such imagery, and to determine whether this method is helpful in analyzing karstic landforms and speleogenesis. Available imagery included: (1) low-altitude, black-and-white (panchromatic) prints, (2) a controlled photomosaic, (3) high-altitude, color-infrared transparencies, and (4) black-and-white (Band 5) LANDSAT (ERTS) imagery.

Lineaments are visible where fractured rocks crop out or where they are near enough to the surface to transmit structural patterns through the overburden. Lineaments commonly reflect (1) changes in substrate, regolith, and soil in the vicinity of frac-

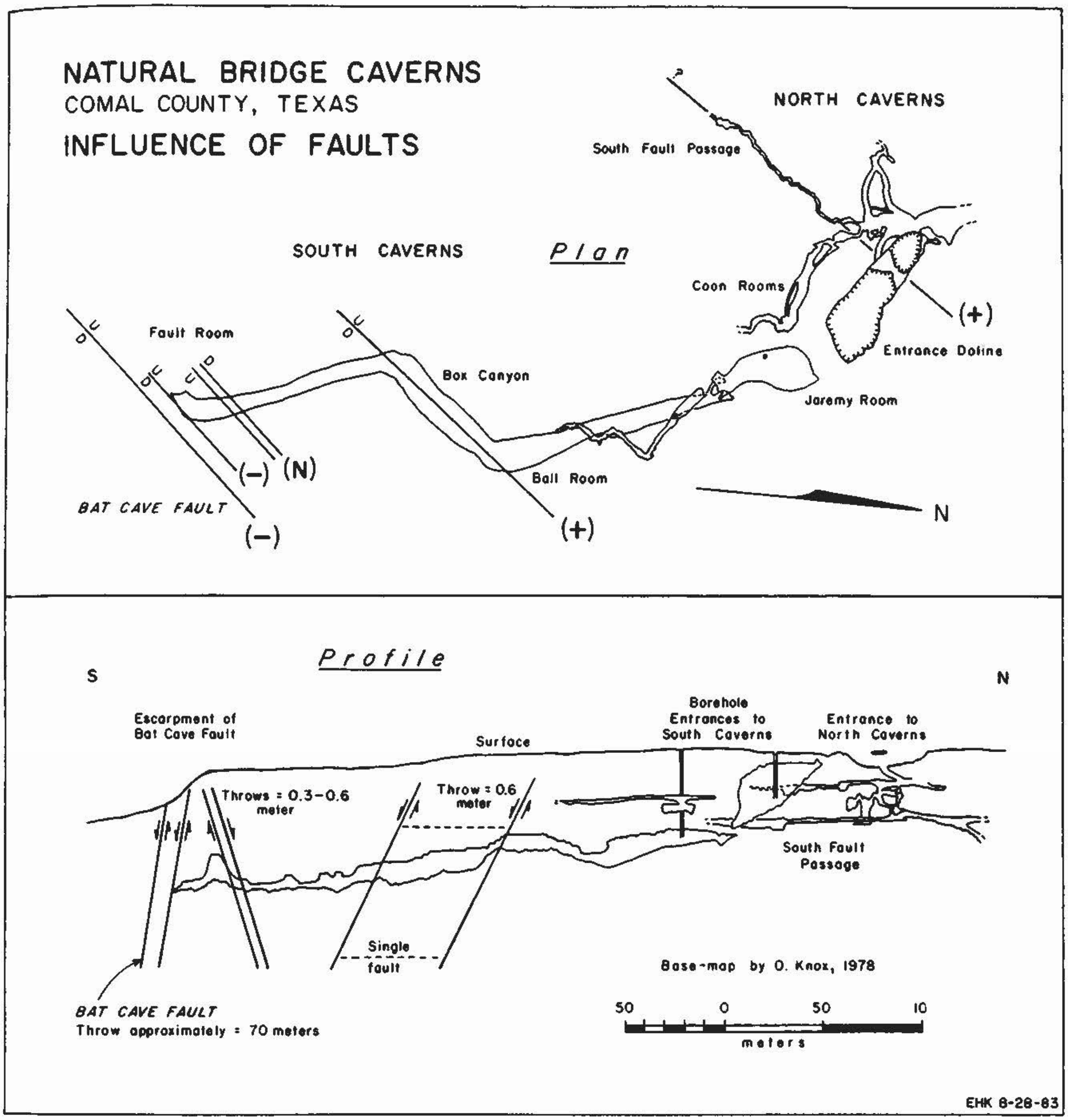

Figure 4. Plan and profile of the South Caverns, Natural Bridge Caverns System, showing faults. Plus sign (+) indicates fault has provided permeable zone for speleogenesis. Negative sign (-) indicates fault has prevented flow of groundwater across it. N indicates fault has not affected flow of groundwater during speleogenesis. Throws are indicated in meters. From Kastning (1983).

tures, (2) patterns in vegetation due to availability of moisture in fractures, (3) differences in moisture within surficial material on opposite sides of a fracture, and (4) changes in the albedo of the surface owing to retention of moisture in fractures. Although most fractures can be discerned on the ground, some are too extensive or subtle to be recognized easily in this way. However, these may be readily detected and mapped from aerial, suborbital, or orbital platforms.

A comparison of the map of fractures with known faults on geologic maps shows that many lineaments parallel the Hidden Valley, Zaccaria Ranch, Zuercher Ranch, Bat Cave and Hueco Springs Faults of the Balcones Fault Zone. A second prominent set of lineaments trending N 10°-40° W represents fractures associated with the San Marcos Arch. Numerous shorter lineaments on the map are orthogonal to fractures of the two prominent sets, and may be regarded as conjugate fractures associated with the Balcones Fault Zone and San Marcos Arch.

Orientations of mapped photolineaments and of linear segments of passages in caves may be compared from rose-diagrams (Figure 5). It is readily seen that the orientations of passages have been largely guided by fractures.

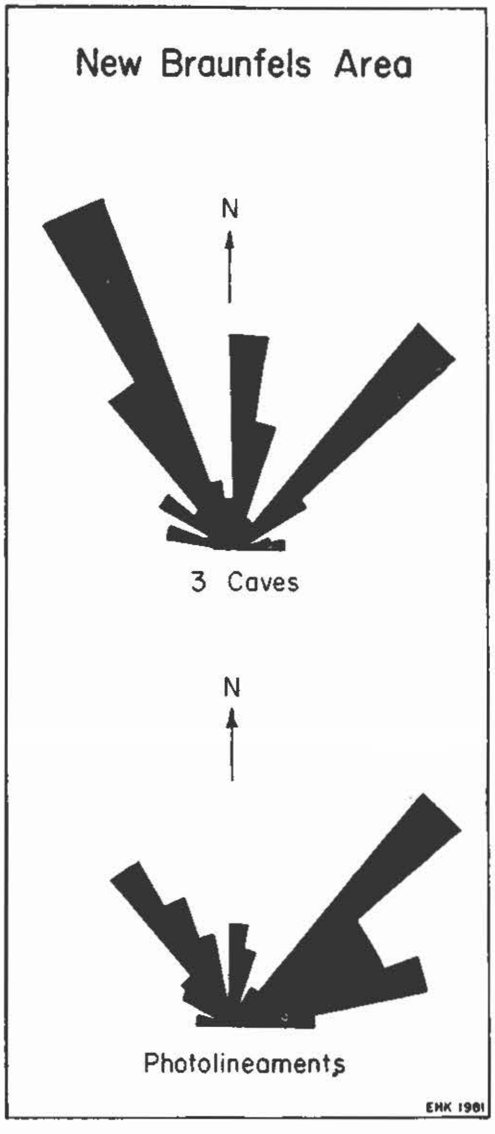

Figure 5. Rose-diagram indicating orientations of mapped photolineaments (from both high and low altitude imagery) and orientations of mapped passage segments in Natural Bridge Caverns, Bracken Bat Cave, and Double Decker Cave. From Kastning (1981, 1984).

Modification by Collapse

Each of the three caves discussed above exhibits significant modification through the collapse of ceilings of the original conduits. Nearly all of the large chambers of the Natural Bridge Caverns System are floored by mounds of debris from collapse (Figure 2). Zones of collapse are evident in the vicinity of the Entrance Pit and along the Upper Level of Double Decker Cave. The slope within the doline at the entrance to Bracken Bat Cave is floored with debris from collapse, and a mound of breakdown occurs 80 m into the cave.

Presumably, bouyant forces provided by phreatic water were removed as the caves drained, allowing collapse of ceilings previously weakened by joints and solutional enlargement of conduits. Continued collapse promoted upward stoping of passages until mechanical stresses were stabilized in accordance with the present configurations of passages. Stoping occurred along the entire length of the master conduit in the lower levels of the Natural Bridge Caverns System (Figure 2), but large rooms of collapse, termed "breakout-domes", are localized in areas of intense fracturing. Commonly such rooms have formed where two or more prominent fractures intersect (Figure 2), suggesting that such intersections greatly weaken beds of the ceiling. The Hall of the Mountain Kings is a "textbook example" of a breakout-dome, similar in form to those found in Mammoth Cave in Kentucky (White and White, 1969) and Wyandotte Cave of Indiana (Malott, 1951, p. 33). Stoping in Natural Bridge Caverns has transgressed beds of the Walnut Formation and progressed 6 m into the overlying Kainer Formation. Ceilings are remarkably flat and elliptical, and walls are flared in a mechanically stable configuration.

The most massive collapse and stoping occurred in the vicinity of the entrance to Natural Bridge Caverns. Here stoping progressed from the Glen Rose Formation, through the overlying Walnut and Kainer Formations, and intersected the surface, forming the doline at the entrance. The Natural Bridge, namesake of the cave, is a remnant which has not yet collapsed. The northern end of the South Caverns, Jaremy Room, and Pluto's Anteroom all lie on the flanks of the large mound of debris remaining from collapse (Figure 2). The doline at the entrance to Bracken Bat Cave has formed in an identical manner.

The volume of debris in mounds within the breakout-domes is generally less than that of the material which has collapsed. This suggests that much of the debris has been removed by dissolution. Waters may have gradually drained from the caves over a considerable period of time so that, as bouyant forces were removed, there was still sufficient circulation of water through the lower parts of the chambers to remove material from collapse. Alternatively, vertical fluctuations of waterlevels may have been sufficient over a long time to allow collapse and concomitant dissolutional removal of debris.

Collapse has greatly modified the flow of vadose water through conduits of Natural Bridge Caverns. River Styx and Purgatory Creek have been diverted away from the master conduit in areas of collapse, and emerge only in the lowest points of the cave where collapse has been minimal. Water rising from these streams during severe flooding is retained behind dams created by the mounds of debris.

Speleothems

Speleothems in the Natural Bridge Caverns System range in size from massive stalagmites and mounds of flowstone to slender, sodastraw-stalactites. Sodastraws in the Fault Room average 0.5 to 2 m in length and one specimen, suspended from the high ceiling of this room, is over 4.3 m in length, one of the longest known in the world. Sodastraws form comparatively rapidly (as much as a few millimeters in length per year, and these formations are relatively recent features associated with slow, vertical seepage along joints. The massive formations of the Castle of the White Giants, on the other hand, are substantially older and still actively forming.

As with other speleothems in caves of the Edwards Plateau many of those which are no longer active show evidence of redissolution. Redissolved stalagmites are common at all levels of the caves, but are more numerous in the Hall of the Mountain Kings in Natural Bridge Caverns. Some stalagmites have been reshaped into streamlined forms by flowing water. The large stalagmites in the Castle of the White Giants have solutional hollows created by redissolution.

Redissolved formations are found as high in the cave as the top of the Walnut Formation in the Hall of the Mountain Kings. Although redissolution may in part be from periodic flooding in lower levels, it is likely that much of this activity is caused by condensation-solution attributable to movement of humid air through the caves. This phenomena has recently been recognized in the caves of the Guadalupe Mountains of New Mexico and far west Texas.

CONCLUSION

The developmental history of the three caves proceeded according to the following chronological sequence:

1. The San Marcos Platform was raised episodically along its northwestern axis throughout the post-Albian Cretaceous, producing a system of fractures parallel to its axis. Subaerial exposure of the platform in the late Albian resulted in removal of over 30 m of uppermost beds of the Edwards Group, steepening of hydraulic gradients, and circulation of groundwater through fractures. Flow of groundwater was primarily to the south, and original pores were subsequently enlarged into poorly integrated cavities (Woodruff and Abbott, 1979).

2. During the remainder of the Cretaceous, the region was alternately covered by shallow, marine, shelfal waters and exposed to subaerial conditions. Indications of the latter include (1) absence of the Del Rio Clay just west of New Braunfels (where the Buda Limestone rests unconformably on the Georgetown Formation), (2) absence of the lower members of the Austin Chalk on the San Marcos Arch, and (3) presence of Upper Cretaceous rocks (e.g. Austin Chalk) as fill within dolines in units older than those of the Eagle Ford Group. Although further accentuation of the San Marcos Arch in the Late Cretaceous continued to produce fractures, speleogenesis in the area of the Natural Bridge Caverns System was substantially curtailed under conditions of reduced porosity and in the absence of steep hydraulic gradients in the evolving aquifer.

3. The region was lifted above sealevel near the close of the Cretaceous, and rocks attained a gentle (less than 0.5°) southeastward dip. However, an absence of nearby points of discharge precluded development of sizeable solutional conduits.

4. Regional (Balcones) faulting during the Miocene significantly accelerated the geomorphic evolution of drainage on the surface and in the subsurface. Northeast-trending fractures produced during faulting were overprinted on the pre-existing north-west-oriented set of fractures. The Balcones Escarpment established a low baselevel to the southeast toward which surficial and subsurficial geomorphic processes began to operate.

5. Flow of groundwater increased in response to steepened hydraulic gradients created by drainage to springs at baselevel along the Balcones Escarpment. Some faults, such as the Bat Cave Fault, imposed impermeable boundaries on the aquifer, diverting groundwater along the strike of the faults. Flow along fractures and bedding-plane partings within the phreatic zone became integrated into master conduits, producing some of the larger passages of caves. These include the main passage along the lower level of the Natural Bridge Caverns System, the large passage of Bracken Bat Cave, and the Upper and Lower Levels of Double Decker Cave. Some conduits followed beds of favorable primary and solutionally enhanced porosity, and became oriented down the dip, in the direction of greatest hydraulic gradient. However, other passages cut across previous solutional cavities. Most conduits were strongly guided by fractures of the two primary sets. Formed by tensional stresses during uplift of the San Marcos Arch and faulting along the Balcones Fault Zone, these fractures were sufficiently open to easily accommodate phreatic flow. In places, dip-oriented conduits at different levels were integrated through vertical chimneys along fractures, allowing flow to move continuously through a single solutional channel from one stratigraphic horizon to the next. This situation is exemplified by Double Decker Cave where flow was communicated from one level to the other along a major fault.

6. As conduits enlarged, their widths became too great to support overlying beds, and collapse of ceilings began. This may have been initiated as water first began to drain from the caves, removing bouyant support of the ceilings.

7. The potentiometric surface in the aquifer began to drop as surficial streams became entrenched along the escarpment and as a consequence of the capture of streams (Woodruff and Abbott, 1979). The caves began to drain as the dropping potentiometric surface intersected the conduits. Mounds of debris in the caves were partially removed by vadose waters still flowing in the conduits. Areas of collapse became mechanically stabilized.

8. Speleothem deposition began.

9. Increased precipitation and decreased evaporation during pluvial climates of the Pleistocene resulted in high discharges in the existing caves. Collapse and alluviation within the caves prevented efficient throughflow of groundwater. As a consequence, caves underwent periodic flooding which locally promoted development of routes of bypass for floodwater around mounds of debris previously created by collapse. Smaller, middle- and upper-level passages in the Natural Bridge Caverns System developed as routes of bypass in response to blockages. Preexisting conduits were also enlarged by floodwaters.

10. Vadose flow in the caves diminished to present levels with the advent of warmer climates. This flow apparently represents underflow derived from recharge along Cibolo Creek. Under conditions of baseflow, discharge is carried through inaccessible conduits beneath the explored levels of Natural Bridge Caverns.

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POST-MIOCENE CARBONATE DIAGENESIS OF THE LOWER CRETACEOUS EDWARDS GROUP

IN THE BALCONES FAULT ZONE AREA, SOUTH-CENTRAL TEXAS

Patricia Mench Ellis
Department of Geological Sciences
University of Texas at Austin
Austin, Texas 78712*

ABSTRACT

This study documents the diagenetic history of the Lower Cretaceous Edwards Group in the Balcones fault zone area of south-central Texas. The Edwards Group consists of 400 to 600 feet of porous limestone and dolomite that accumulated on the Comanche shelf in shallow-water subtidal, intertidal, and supratidal marine environments. During early diagenesis, carbonate mud neomorphosed to calcitic micrite, aragonite and Mg-calcitic allochems were altered to calcite or were leached, and evaporites formed in tidal-flat sediments. Dolomite is widespread and formed in environments ranging from hypersaline to fresh water.

Faulting along the Balcones fault zone initiated a circulating, fresh-water aquifer system to the west and north of a fairly distinct "bad-water line," which roughly parallels the Balcones fault zone. To the south of the bad-water line, interstitial fluids remained relatively stagnant and contain over 1000 mg/l dissolved solids. Because of the differences in the chemistry of the interstitial fluids, post-faulting diagenesis in the two zones has been very different. Water in the bad-water zone can be saturated with respect to calcite, dolomite, gypsum, celestite, strontianite, and fluorite; whereas water in the fresh-water zone is saturated only with respect to calcite. Due to the change in water chemistry, rocks in the fresh-water zone have been extensively recrystallized to coarse microspar and pseudospar, extensive dedolomitization has occurred, and late sparry calcite cements have precipitated. In contrast, rocks in the bad-water zone retain fabrics associated with pre-Miocene diagenesis.

The importance of diagenesis in shallow, subsurface environments is illustrated by the fact that the Edwards Group had a stable mineralogy of calcite and dolomite before the circulation of fresh water began. In spite of the "stable" mineralogy, considerable additional diagenesis occurred in the fresh-water zone, and probably continues to occur today.

INTRODUCTION

This study approaches the problem of documenting and understanding the diagenetic history of the Edwards Group carbonates in the Balcones fault zone area by petrographic study and by the use of various geochemical techniques. A wide variety of depositional environments were represented, from high to low energy, with restricted to open circulation. Environments tended to be patchy in lateral extent, but in a vertical direction environmental trends had more continuity.

Several questions were addressed during this study. What are the petrographic characteristics of various diagenetic components, and what processes were responsible for their formation? Can the timing of diagenetic events be related to various tectonic and stratigraphic events in the history of the rock?

General Geology of the Study Area

During the Late Jurassic and Cretaceous, regional subsidence of the Gulf of Mexico basin resulted in the deposition of an arcuate prism of sediments which thickens from a few hundred feet updip to more than 10,000 feet along the ancient shelf margin 100 to 300 miles downdip (McFarlan, 1977). During most of the early Cretaceous, a ridge complex of biogenic reefs, banks, tidal bars, channel fills, and islands existed on the shelf edge that separated the shallow-water interior of Texas from the deeper-water Gulf of Mexico basin. This band is commonly called the Stuart City reef trend (Winter, 1961; Bebout and Loucks, 1974), and is composed of rudist, coral, and algal debris. To the southeast, sediments sloped into the deeper waters of the ancestral Gulf of Mexico. Shallow-water carbonates of the Edwards Group were deposited on a generally submerged plain called the Comanche shelf (Rose, 1968) in environments ranging from open marine waters to arid, hot, supratidal flats. Typical shallow-water, restricted carbonate facies were deposited on this shelf: they shifted positions gradually with time. Euxinic and evaporitic deposits occurred to the west, and shallow marine carbonate rocks elsewhere. Over the broad axis of the San Marcos platform, shallow marine carbonates and dolomitic tidal flat deposits are present. Between the tidal flat deposits and open shelfal beds occur shallow marine calcarenitic banks and bioclastic beds. The San Marcos platform influenced facies tracts on the Comanche shelf more than did the Stuart City reef. The Edwards is a wide belt of shallow-water sediments deposited behind marginal banks, with the lateral succession of facies reflecting increasing restriction toward the axis of the Central Texas platform. Sedimentation of the Cretaceous strata of Texas was controlled by a combination of structural and regional stratigraphic features.

The study area follows the trend of the Balcones fault zone, a series of <u>en echelon</u>, high-angle, down-to-the-coast normal faults which forms an arc averaging 10 to 12 miles in width and paralleling the trend of the underlying Ouachita system as it bends around the Texas craton (Figure 1). The area is approximately 175 kilometers long and 50 kilometers wide, and is enclosed by two groundwater divides, one

* Current address: 1015 Sherfield Ridge Drive, Katy, Texas 77450

in Abbott, Patrick L. and Woodruff, C.M., Jr., eds., 1986, **The Balcones Escarpment, Central Texas**: Geological Society of America, p. 101-114

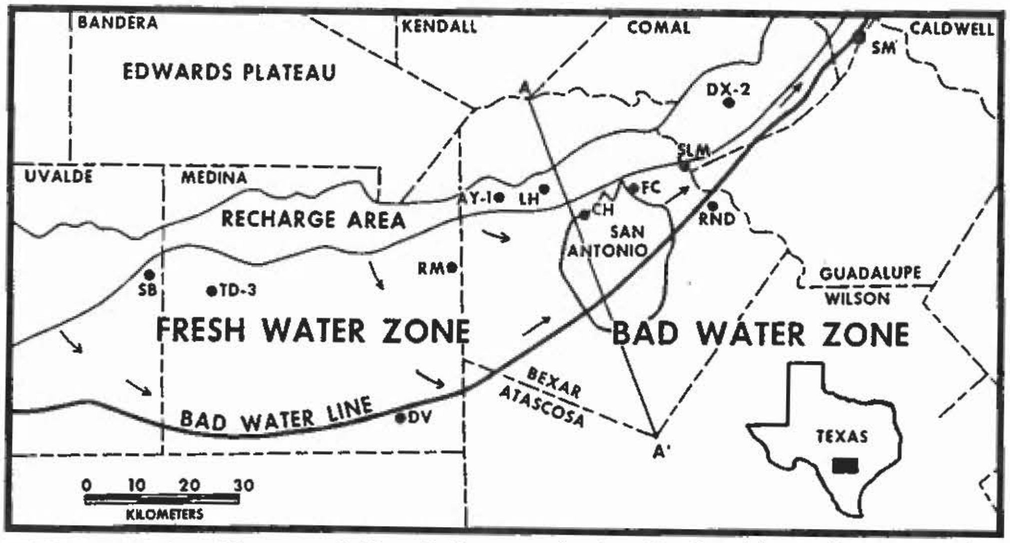

Figure 1. Location map of the study area showing the locations of cores used in the study, the location of the Edwards Aquifer with approximate flow directions, the zones of fresh-water, bad-water, and the "bad-water line."

in Kinney County near Brackettville, and the other in Hays County near Kyle, which were considered to be the end boundaries of the aquifer (Garza, 1962b). Facies patterns within Comanchean rocks show no effect of Balcones fault movement during their deposition. The first positive evidence of movement on the Balcones fault system is shown by the abundant reworked Upper Cretaceous fossils and limestone fragments in the Lower Miocene Oakville Formation (Weeks, 1945; Ragsdale, 1960). It seems that most Balcones faulting was restricted to the Miocene (Young, 1962). Well cores were available along this fault trend in Hays, Comal, Bexar, Medina, and Uvalde counties. Three cores were available from the bad-water zone, and nine from the fresh-water zone. Previous studies have shown that the lithology, porosity, and textures of carbonates in the two zones are quite different. This study was undertaken to relate the diagenesis of the Edwards to the geochemistry of the original and later pore waters as they evolved in the system. Descriptions of techniques used in this study may be found in Ellis (1985).

General Hydrology of the Edwards Aquifer

Regional Movement of Groundwater in the Edwards Aquifer

The Edwards Aquifer is approximately 175 miles in length. It varies in width from 5 to 40 miles, and in thickness from 400 to 700 feet (Figure 1). It lies along the Balcones Escarpment, formed by the Balcones fault zone, a series of normal faults along which the Gulf Coastal Plain has been dropped relative to the Edwards Plateau. Water entering the Edwards Aquifer moves generally southward across the reservoir outcrop and then eastward through the artesian zone of the aquifer toward areas of natural discharge.

The Edwards fresh-water aquifer forms two distinct reservoirs in south-central Texas; the unconfined aquifer under the Edwards Group on the Edwards Plateau, and a confined aquifer (Edwards underground reservoir) associated with the Balcones fault zone. The southeastern boundary of this aquifer is a marked and mappable "bad-water line." The bad-water line marks the transition from potable fresh water of the Edwards Aquifer to the non-potable brackish water of the bad-water zone. The boundary is usually well defined and has been traced from Comal County, Texas, into northern Mexico (Back and Hanshaw, 1977). The boundary trends northeast, similar to the strike of the Balcones faults, although for much of its length it does not appear to be fault-controlled.

No springs discharge south and east of the bad-water line, and yields from wells are considerably lower there. Apparently the only natural discharge from the region is slow upward seepage. The bad-water line formed as a bypass boundary that meteoric water moving under structural or hydrologic controls did not transgress. What originally may have been a random hydrologic flow boundary became more ingrained with time (Abbott, 1975).

The position of the bad-water line is largely a function of the availability of water during and shortly after the uplift owing to Balcones faulting, as the present groundwater regime was being established. The active circulation, with flushing and solution on the upgradient side, developed a major fresh-water aquifer.

Water Chemistry of the Edwards Aquifer

Water analyses were published by Pearson and Rettman (1976). They categorized the waters into five groups to show differences in the capacity of the waters to dissolve and precipitate carbonates and other minerals. For simplicity, I will summarize the characteristics of only two of their water groups - the recharge and main fresh-water groups combined, and the saline or "bad-water" group.

The fresh-water zone has total dissolved solids less than 1000 mg/l, and is generally in the 250-350 mg/l range. Sulfates and sulfides are low. The water in this zone is strongly oxidizing. Water is of the calcium bicarbonate type, in which the chloride content is generally less than 25 mg/l. Within the fresh-water zone the ratios between the different dissolved constituents are everywhere similar. Edwards aquifer fresh water is saturated with respect only to calcite. The pH of water in the fresh-water zone ranges from 7 to 7.6. Flow in the main fresh water-bearing part of the Edwards is so rapid that the geothermal gradient is suppressed and water temperatures vary only over the narrow range of 22 to 27°C. The chemical homogeneity and lack of a normal temperature-gradient reflect the rapid movement of water through the aquifer in fractures and solution channels. Well production is characterized by high flow rate and little or no drawdown.

Downdip, the chemistry of the water changes abruptly. It becomes strongly reducing, has a high sulfate content, and contains considerable quantities of hydrogen sulfide. In the saline zone, water pH is commonly less than 7.0. The saline, or "bad-water" zone, is defined by total dissolved solids in excess of 1000 mg/l, and they frequently exceed 4000 mg/l. Calcium and sulfate ions are the major cation and anion. The water is strongly reducing and can have 50 mg/l or more H_2S. Sulfates are as high as 2000 mg/l. Ratios and absolute concentrations of all major ions change markedly across the bad-water line. All major dissolved constituents increase in concentration in the saline zone, and Na^{+1} and Cl^{-1} become major ions in solution. In the bad-water zone the water is saturated with respect to calcite and dolomite. Some of the waters from this zone also were saturated with respect to gypsum, celestite, strontianite, and fluorite. From the fresh-water zone there is little downdip flow through the transitional zone and into the saline zone so water temperatures there increase and reach values of 47°C, close to the expected geothermal gradient.

The chemistry of the bad-water zone is controlled by mixing of water from the fresh-water zone updip and deep water downdip. Deep subsurface water, downdip from the bad-water zone, consists of chloride-calcium brines with a Na^{+1}/Ca^{+2} ratio less than 1 and $(Cl^{-1}-Na^{+1})/Mg^{+2}$ greater than 1 (Prezbindowski, 1981). Water in the fresh-water zone averages about 1/100th the salinity of sea water, and water in the bad-water zone ranges from 1/35th to 1/4th the salinity of sea water. The Mg/Ca molar ratio increases from less than 0.5 in the fresh-water zone, to 1.0 in the saline zone. The transitional waters are not simple mixtures between the extreme types, but result as fresh water flows downgradient into rock of a different mineralogic makeup and, with flow, react with this rock until water-rock equilibrium is established. The reaction driving the changes in chemistry in the transition zone and producing the marked mineralogic and petrographic changes in the Edwards, is the dissolution of gypsum. The effects of these reactions are seen in the mineralogy of rocks of the fresh- and bad-water Edwards carbonates. In the bad-water cores, dolomite is the dominant mineral and gypsum is present; little alteration has occurred. The original organic material, sulfides, and evaporites have been preserved. In the fresh-water cores, calcite dominates over dolomite, and gypsum is rare. Sulfides and carbonaceous material have been oxidized.

CRETACEOUS DIAGENESIS IN THE EDWARDS GROUP

Early and late stages of diagenesis have been recognized in the carbonates of the Edwards Group. Many workers have studied diagenesis in the Edwards Group, however, except for studies by Mench (1978), Longman and Mench (1978a,b), Mench and others (1980), Ellis (1985), Pearson and others (manuscript in prep.), only Abbott (1973, 1974) has studied Edwards diagenesis in the Balcones fault zone. "Early" diagenesis occurred from the time of sediment deposition until Balcones faulting in the Miocene, and "late" diagenesis occurred from the time of Miocene faulting to the present. Early diagenesis will be briefly discussed, omitting details of evaporite formation and silicification. (See Ellis (1985) for details of pre-Miocene diagenesis.) Late diagenesis, including neomorphism, dedolomitization, and the formation of late sparry calcite cements, will be discussed in greater detail.

Figure 2. Cretaceous submarine cementation of a molluscan-intraclast grainstone by polygonal calcite cement. The boundaries where the cement meets in the intergranular spaces are thin and suture-like with triple junctures. The cement is fibrous, averaging 0.15 mm. in thickness. The long dimension of photograph is 1.7 mm. Plane-polarized light. Core DX-2, sample from 304 feet.

Diagenesis in the Marine Environment

Carbonate allochems wererounded and broken in the environment of deposition either by physical abrasion and/or biological degradation. Micrite envelopes are a common feature of fossil fragments in skeletal grainstones in the Edwards, but are relatively rare or poorly developed in the Edwards packstones, wackestones, and mudstones.

Very few examples of submarine cementation were found within the study area. These cements are fibrous to bladed and show polygonal sutures of cement as described by Shinn (1975) (Figure 2). Folk (1984, pers. comm.) suggests that marine cements in Cretaceous seas were calcites with 2-10% Mg (not 15-20 percent as in modern marine cements). Isotopic analyses of Edwards Group samples (Figure 3) fall within the expected ranges for marine cements (Hudson, 1977); electron microprobe traverses show a slight Mg^{++} memory.

Diagenesis in Meteoric Phreatic and Subsurface Environments

When Edwards Group carbonates were exposed to Cretaceous fresh water in the meteoric zone, diagenesis was extensive. Aragonite needles neomorphosed to calcite and became more equant. Magnesium ions were flushed from the grains of magnesian calcite. Continued flushing led to complete recrystallization and the transformation to an interlocking mosaic of small calcite crystals. Mg-calcite shells have lost their Mg without noticeable alteration of shell microstructure. Aragonitic allochems, unstable in the presence of meteoric water, are most commonly dissolved and later refilled with sparry calcite. Dissolution of aragonite did not take place everywhere in the Edwards Group at the

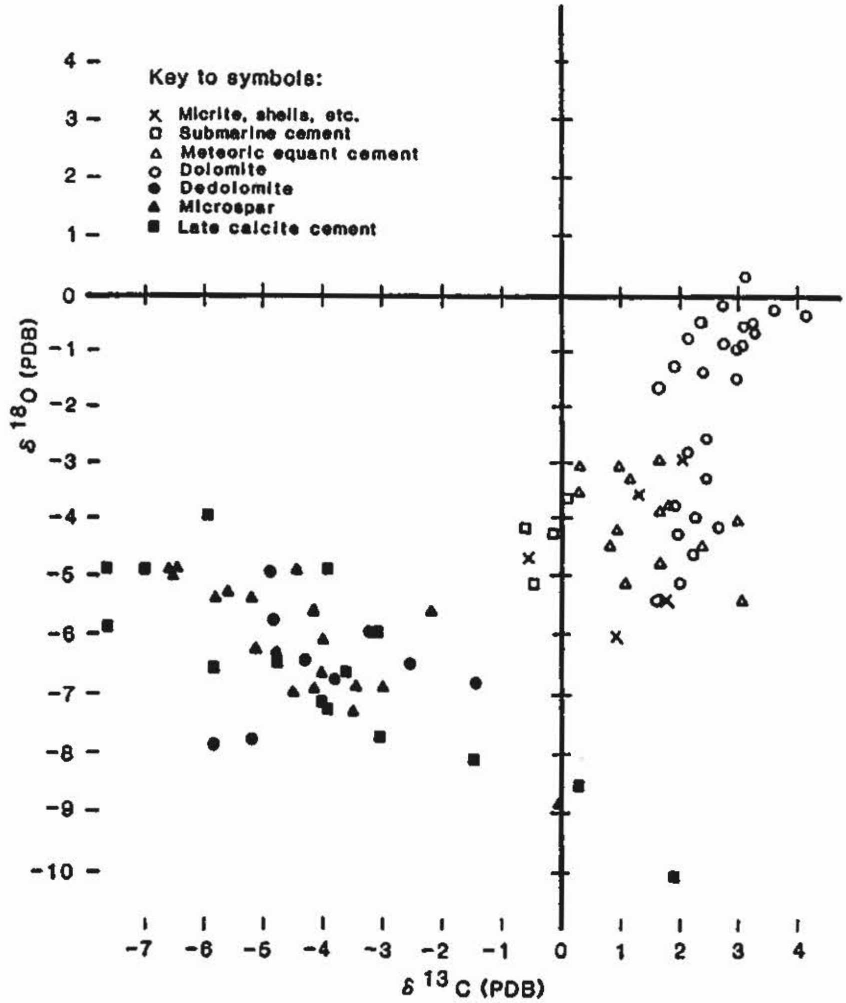

Figure 3. A cross-plot of $\delta^{18}O$ (PDB) with $\delta^{13}C$ (PDB) composition for selected samples from the Edwards Group, Balcones fault zone area showing clustering of data for Cretaceous-related diagenetic products (open symbols) and Miocene to Recent-related diagenetic products (solid symbols).

same position in the diagenetic sequence. Most commonly, dissolution of aragonite followed precipitation of a thin layer of equant, medium crystalline, calcitic cement, and preceded deposition of a later, coarser equant calcite cement which also partially or completely filled the aragonite mold.

Fine- to medium-crystalline, bladed to equant, isopachous, calcitic cement (Figure 4) averaging 0.1 mm thick is the most common type of cement in Edwards grainstones. This type of cement precipitated in a meteoric phreatic environment, from waters with a Mg/Ca ratio of less than 2:1 and probably less than 1:1 (Folk, 1973, 1974; Folk and Land, 1975). Electron microprobe analyses of these cements showed low amounts of magnesium, which was to be expected in a meteoric phreatic environment.

The formation of more coarsely crystalline, equant calcite cement, usually from 0.2 to 0.4 mm in size, followed the deposition of isopachous rim-cement (Figure 5). The equant calcite cement is separated from the earlier cement by a distinct break in crystal size, and a slight decrease in Mg^{++} content. Waters with a Mg/Ca ratio below 1:1 were probably responsible for this phase of cementation (Folk, 1973, 1974; Folk and Land, 1975). The isotopic compositions of equant, calcitic cements (Figure 3) average $\delta^{18}O = -3.81$ and $\delta^{13}C = +1.38$. Comparison of these values with those found for submarine cement shows the equant calcite to be slightly enriched with respect to both carbon and oxygen, even though they formed in fresher waters. I believe that the submarine cements are showing effects of some isotopic exchange because their original composition would be unstable when exposed to fresh water. Also, some of the examples of submarine cement show petrographic evidence of minor recrystallization. Whether this recrystallization was due to fresh water present at the time of formation of early calcitic cements, or whether it is due to flow of fresh water related to Miocene faulting, or both, cannot be determined with certainty. Early calcitic rim-cements probably result from the dis-

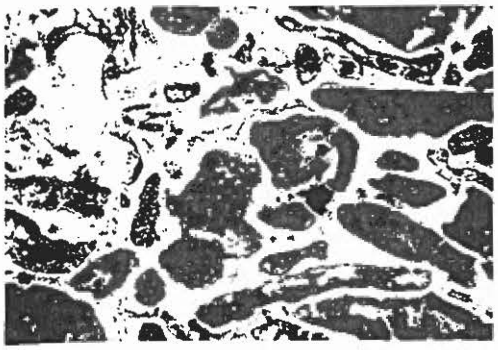

Figure 4. Typical Cretaceous meteoric phreatic cement. Fine to medium crystalline, isopachous, calcitic cement is the most common type of cement in Edwards grainstones. The crystals are bladed to equant, evenly surrounding the framework grains. The long dimension of photograph is 4.1 mm. Cross-polarized light. Core DX-2, sample from 312 feet.

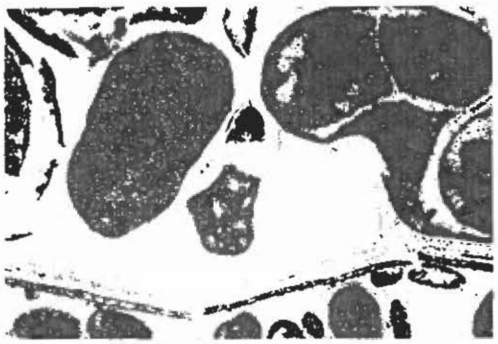

Figure 5. Photomicrograph shows two generations of Cretaceous meteoric phreatic cement in a miliolid-intraclastic grainstone. The first cement is a fine, isopachous, equant, calcitic cement. Some compaction took place after the formation of this cement as evidenced by the spalling cement near the center of the photograph. Later, a coarsely crystalline, equant, calcite filled the remaining pore-space. The long dimension of photograph is 4.1 mm. Plane-polarized light. Core TD-3, sample from 313.5 feet.

solution of aragonite and the stabilization of magnesium calcite in the meteoric phreatic environment. Petrographic evidence demonstrates most, but not all calcitic rim cements, to be precompaction. Later cements may derive a proportion of their material from carbonate released during pressure-solution and carried in from nearby rocks. The presence of relatively low compaction and high primary porosity in some Edwards rocks is a result of precompaction cementation.

Dolomitization

Petrography and Petrology of Dolomites

Originally both the fresh-water zone and the bad-water zones contained significant quantities of dolomite. However, dedolomitization has affected much of the dolomite in the fresh-water zone. Edwards Group dolomite varies from finely crystalline, dirty, anhedral to subhedral crystals finer than 0.01 mm, to medium crystalline, clear, subhedral to euhedral crystals as large as 0.1 mm. Several types of dolomite have been recognized in rocks of the bad-water zone (Longman and Mench, 1978a, b). The onset of dolomitization occurred after stabilization of Mg-calcite.

Much of the porosity in dolomites of the Edwards Group formed as a result of incomplete dolomitization of muddy sediments. Following partial dolomitization, any undolomitized micrite was then dissolved by fresh water. The intercrystalline porosity thus formed in the dolomites has been measured to be as high as 43%, and values are frequently in the 25-35% range (Ellis, 1985). In addition, permeabilities in these porous dolomites can be quite high.

Dolomite interpreted to have formed penecontemporaneously in supratidal sediments generally appears as small (less than 4 microns) rhombs with abundant inclusions; originally it probably was protodolomite. Dolomite crystals with "dirty" cores and cleaner rims are common. During diagenesis, the interstitial water changed from hypersaline to relatively fresh, but dolomite rhombs apparently continued to grow in spite of the change, forming clear euhedral overgrowths (Folk and Siedlecka, 1974). Later, in lower-salinity waters, the chemical stability of the original core of protodolomite was apparently less than that of the surrounding overgrowths, so as a result, hollow dolomite rhombs are common. Kerr (1976) also reported zoned, hollow dolomite in his study of the Edwards Group in Belton quarry.

Limpid dolomite with perfect rhombic shape and mirror-smooth crystal faces (described by Folk and Siedlecka, 1974) in the Edwards Aquifer was a relatively late-stage dolomite. It tends to form as overgrowths on other forms of dolomite and also to line cavities and shell molds formed by leaching (Figure 6). It did not often form in micrite but instead preferred open spaces. This suggests that leaching of micrite preceded the formation of limpid dolomite.

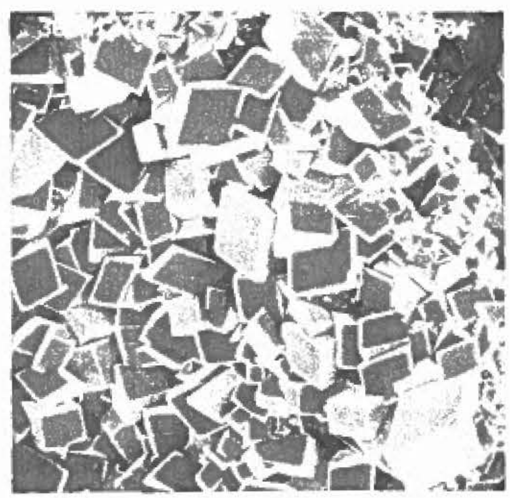

Figure 6. Limpid dolomite crystals lining a cavity formed by the leaching of a mollusc shell. Note remarkably smooth crystal faces. Scanning electron photomicrograph. The long dimension of photograph is 240 microns. San Marcos core, sample from 504 feet.

Stable Isotope Geochemistry of Edwards Group Dolomites

A crossplot of $\delta^{18}O$ with $\delta^{13}C$ values of Edwards Group dolomites (Figure 3) shows a linear trend. Values of $\delta^{13}C$ vary within a small range, from +1.62 to +4.10, with an average of +2.57. Values of $\delta^{18}O$ vary over a fairly wide range, with -5.41 being the lightest value and +0.32 the heaviest (average value is -1.98) (Mench and others, 1980; Ellis, 1985). The most ^{18}O enriched dolomites come from the more gypsiferous members of the Edwards and tend to be typical hypersaline dolomites. These dolomites are fine-grained, cloudy crystals, commonly occurring in supratidal sequences and were probably originally protodolomite. The most ^{18}O depleted samples of dolomite are primarily limpid dolomites, associated with waters of low salinity.

Model for dolomitization in the Edwards

Petrographic, petrologic, and geochemical evidence from this study support the hypothesis that Edwards dolomites were formed by at least two episodes of dolomitization (Ellis, 1985). The first episode was very early, produced from hypersaline brines, with location being controlled by depositional facies. The second episode was later, but with the location still mostly controlled by the location of nuclei from the earlier hypersaline dolomitization. For many dolomites the cores formed rapidly from hypersaline brines, so that magnesium was not incorporated into the lattice in stoichiometric proportions. The rims precipitated from less concentrated solutions, and less rapidly, so that magnesium was incorporated in more stoichiometric proportions.

According to the fresh-water-mixing hypothesis, chemically more perfect dolomite forms from dilute solutions. Fresh- and saline-mixed waters also were capable of dolomitizing by themselves, without having hypersaline cores on which to build. This can be seen from the presence of pure, limpid dolomite without hypersaline cores, although mixing zone dolomite more commonly overgrows earlier dolomite.

The present Mg/Ca value of 1:1 in the bad-water zone and salinities ranging from 1/10th to 1/100th that of sea water make the formation of dolomite within the bad-water zone a possibility today. Waters of the bad-water zone are saturated with respect to dolomite whereas these of the fresh-water zone are undersaturated. Dolomite in the Edwards has formed in environments ranging from hypersaline, to schizohaline, to fresh water.

Evaporite Minerals

Evaporite minerals formed both early and late in the history of the Edwards Group. Some are related to early sabkha conditions, others as a replacement of earlier minerals, and some may be forming today within the bad-water zone. Details of evaporite formation may be found in Ellis (1985).

Silicification

Petrographic, petrologic, and geochemical data on the various types of silica, combined with similar data on the dolomites and other diagenetic features of the Edwards Group, suggest a local origin for the silica and penecontemporaneous initiation of most silicification. Many molluscan fragments have undergone some form of silicification, evaporites are frequently silicified, and locally, chert nodules are common. Chert replacement of carbonate rocks must occur under conditions where diagenetic waters are simultaneously supersaturated with respect to silica and undersaturated with respect to carbonate, since much chert replacement involves Si precipitation at the same time as carbonate solution. Details of silicification of Edwards carbonates will be found in Ellis (1985).

MIOCENE AND LATER DIAGENESIS IN THE EDWARDS GROUP

Miocene faulting resulted in the establishment of a circulating fresh-water aquifer system to the north and west of a fairly distinct bad-water line which roughly parallels the Balcones fault zone. The rocks in the fresh-water zone have been extensively recrystallized as a result of the changes in the chemistry of the water to which the rocks were exposed.

Original waters in the rocks were marine (salinity was that of sea water, Mg/Ca ratio around 3:1). Early in the diagenetic history, waters varied from hypersaline (salinity from 1-10 times that of sea water, Mg/Ca ratio from 10:1 to 30:1), to fairly fresh (salinity around 1/10 that of sea water and Mg/Ca ratio from 1:3 to 10:1). Cretaceous fresh water resulted in the formation of meteoric cements and limpid dolomite. Only in the present-day fresh-water zone is extensive microspar and pseudospar found. Land and Folk (1975) proposed the realm of formation of microspar in fresh-water aquifers and lakes to be at a salinity of about 1/100th that of sea water, and a Mg/Ca ratio from 1:3 to 1:10. This salinity was much less than that for the precipitation of early, fresh-water cements. Values measured from the aquifer today give a salinity of about 1/100th that of sea water, and a Mg/Ca ratio of about 1:2 (Pearson and Rettman, 1976).

Neomorphism of Micrite to Microspar and Pseudospar

Coalescive neomorphic spherules

Coalescive neomorphism of micrite to microspar and pseudospar is common throughout all cores of the fresh-water zone, but does not exist in cores of the bad-water zone. Crystals in neomorphosed porous micrite in the fresh-water zone typically are spherical to subspherical and polyhedral. Diameters of the spherical grains vary from 5 to 50 microns. Small crystal faces occur on parts of some spheres but most surfaces are covered by small irregular bumps and pits (Figure 7). In thin-section, each grain of microspar and pseudospar can be seen to consist of a single calcite crystal (Figure 8). Some grains of microspar have distinct crystal faces. They occur in a wide variety of shapes from simple rhombs to complex scalenohedra. Such crystals are most common in relatively nonporous micrites of the fresh-water zone, whereas more porous micrites have subspherical grains.

Microspar spherules are restricted to the fresh-water zone. None were observed in the bad-water zone. This suggests that the formation of the spherules is controlled by fresh-water circulation and that it postdates the establishment of the fresh-water aquifer in the Miocene. The effects of outcrop weathering can be ruled out as a cause of this neomorphism since cores were used in this study. The altered zones do not appear to be related to Cretaceous unconformities or surfaces of exposure. Instead, neomorphism must have occurred in the shallow subsurface at depths of 25-200 meters.

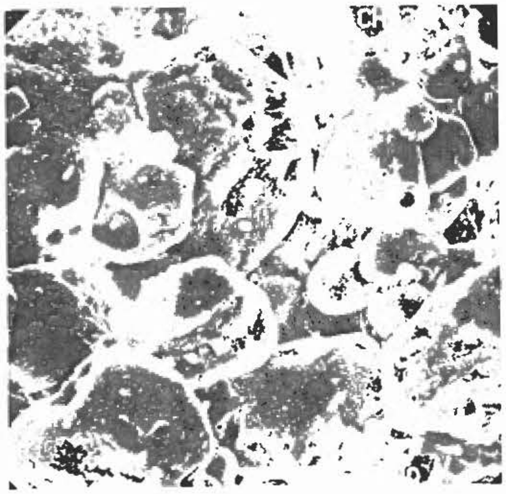

Figure 7. Neomorphism of micrite to spheres of microspar and pseudospar during the Miocene. Diameter ranges from about 5 to 50 microns. Scanning electron photomicrograph. The long dimension of photograph is 90 microns. Castle Hills core, sample from 281 feet.

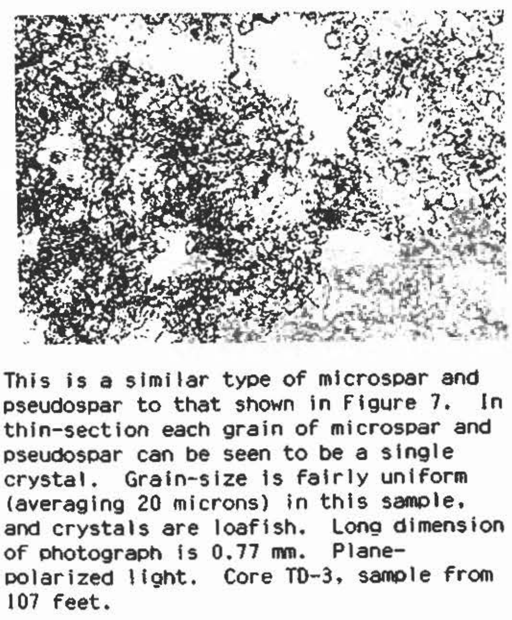

Figure 8. This is a similar type of microspar and pseudospar to that shown in Figure 7. In thin-section each grain of microspar and pseudospar can be seen to be a single crystal. Grain-size is fairly uniform (averaging 20 microns) in this sample, and crystals are loafish. Long dimension of photograph is 0.77 mm. Plane-polarized light. Core TD-3, sample from 107 feet.

<u>Microspar and pseudospar associated with red clay</u>

Clay minerals also play an important role in the formation of microspar and pseudospar, apparently because of their tendency to attract magnesium ions (Folk, 1974; Longman, 1977). By acting as a Mg-ion "sump", the clay "liberates" the calcite micrite from a "cage" of Mg ions and allows it to recrystallize to coarser size. Although clay is sparse in the Edwards Aquifer, patches of Pleistocene terra rossa occur in several cores from the fresh-water zone. These patches are associated with much microspar and pseudospar in grains up to 0.5 mm. long. Microspar grains are tightly packed in these terre rosse and crystal boundaries are difficult to distinguish with the SEM. However, thin sections show the microspar-pseudospar to be loafish or bladed. In areas of higher concentration of clay, crystal size greatly increases and the pseudospar becomes more bladed (Figure 9). Clayey impurities have been segregated

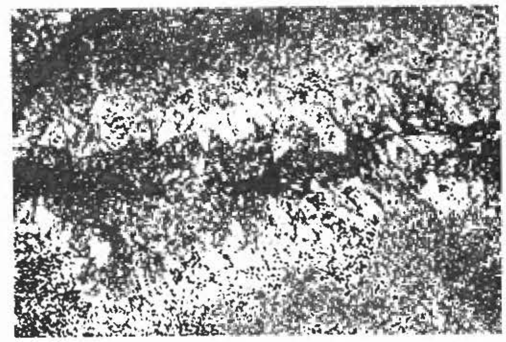

Figure 9. Miocene to Recent microspar in terra rossa clay. The concentration of clay (darker area in center of photograph) has strongly affected the recrystallization of microspar in adjacent areas. In areas of high concentration of clay, crystal size increases greatly and pseudospar becomes more bladed. The long dimension of photograph is 2.2 mm. Plane-polarized light. Castle Hills core, sample from 367 feet.

during neomorphism. In hand specimen the orange patches appear to be largely clay, but in thin section they appear to consist primarily of microspar and pseudospar grains which have displaced small amounts of clay. During the growth of microspar and pseudospar, there is a marginal expulsion of undigested impurities such as clay.

Microspar related to red clay is most abundant in the more porous zones of the fresh-water zone cores located nearest the axis of the San Marcos arch. The area of the San Marcos arch began to rise in early Washita time causing erosion on the surface of the Edwards Group in this area (Rose, 1972). Porosity enhancement in the Edwards was greatest in the exposed area of the Edwards during late Early Cretaceous time. This area was later subjected to greatest fault displacement during the Miocene (Woodruff and Abbott, 1979). The faults and joints superimposed additional avenues for the development of porosity and permeability into an area that already had considerable secondary porosity. Development of porosity continued during the later Tertiary and Quaternary. Terra rossa could have entered the openings thus created after Miocene faulting, but evidence of terra rossa prior to the Kansan is lacking (K. Young, pers. comm., see article in this volume.)

Microspar associated with the clay minerals in the terra rossa can be more accurately dated as to the time of its formation than the rounded microspar spherules formed by the action of interstitial fluids in the porous micrite. Caves along the Balcones fault zone contain many vertebrate fossils of Mid-Pleistocene and younger age but no vertebrate remains older than Pleistocene have yet been found (Lundelius and Slaughter, 1971). This suggests that the terra rossa in the caves must be younger than Pliocene and that the microspar in the terra rossa probably formed in the Pleistocene or Holocene.

<u>Geochemistry of microspar formation</u>

Folk and Land (1975) proposed the realm of formation of microspar in fresh-water aquifers and lakes to be at a salinity of about 1/100th that of sea water, and a Mg/Ca ratio from 1:3 to 1:10, with a salinity much lower than for the precipitation of early, fresh-water cements. Salinities measured from the aquifer today are about 1/100th that of sea water. Mg/Ca ratios are about 1:2 (Pearson and Rettman, 1976).

Rapid flushing throughout the fresh-water zone has resulted in the formation of large amounts of microspar. The flushing could have removed much Mg^{++} from the micritic grains, resulting in their release from their micritic "cage," following which porphyroid neomorphism transformed micrite into microspar and pseudospar (Folk, 1974). Some Mg^{++} removal occurred early in the meteoric zone (Ellis, 1985). Further Mg^{++} could have been removed by clay mineral adsorption as water percolated through the rocks as a result of Miocene faulting. Also, in late diagenesis, flushing of Mg^{++} by fresh water after establishment of the aquifer resulted in the formation of much microspar. Much of this water could have been high in Ca^{++} as a result of solution of evaporites within the formation. This would have further reduced the Mg/Ca ratio. Rocks of the bad-water zone, which were not exposed to late, fresh-water flushing, show no evidence of microspar or pseudospar.

Microspar and pseudospar have among the lowest values of both ^{13}C and ^{18}O in the Edwards (Figure 3), and their values vary inversely, whereas those of the dolomites and early calcites vary together.

It has not been possible to collect samples of the formation water associated directly with the formation of microspar and pseudospar. However, it is possible to compare the isotopic composition of these calcites with that of Edwards water on a regional scale (F.J. Pearson, Jr., pers. comm., 1978) to show that they are in isotopic equilibrium, and so support the contention that the calcites are forming from present-day formation water.

Dedolomitization

Dedolomites are found in all cores of the fresh-water zone. Luster-mottled dedolomites are the most common variety found. Polycrystalline, calcitic rhombs are the rarest type of dedolomite observed. Dedolomites with calcitic centers within dolomitic rims are common in the fresh-water zone, and are found in the bad-water zone only in Randolph core, which is very near the bad-water line. Dolomitic rims without calcitic centers are very common in the bad-water zone, which shows the relative instability of the schizohaline cores, or shows that solution of cores may have occurred in the Cretaceous, before Miocene faulting. Calcite may have grown within these rhombs within the fresh-water, phreatic zone in the shallow subsurface early in the history of diagenesis.

Moore and others, (1968), Abbott (1974), Mueller (1975a), Jacka (1977, 1984), and Prezbindowski (1981) have studied dedolomites within the Edwards Group.

Types of dedolomites in the Edwards Group

Polycrystalline rhombic calcite is a kind of dedolomite in which individual dolomitic rhombs are replaced by a mosaic of finer grained, calcitic crystals (Figure 10). These polycrystalline rhombs of calcite have sharply defined boundaries. This type of dedolomitization occurs by centrifugal replacement. Centers of crystals may have been subjected to calcitization first because they were originally a less stable form of dolomite (Ellis, 1985). Textures indicate that no large void space existed during this replacement. Dedolomites of this type generally occur in porous micrite in the Edwards Aquifer.

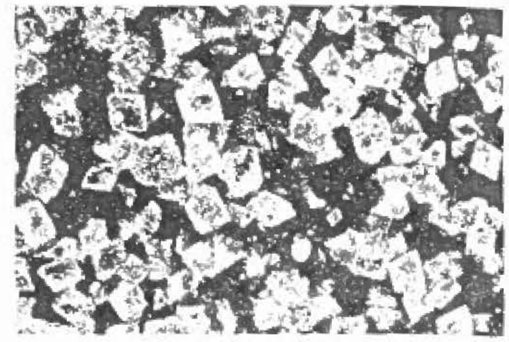

Figure 10. A typical dedolomite which now consists of rhombic polycrystalline aggregates of calcite floating in micrite. The aggregates replaced single crystals of dolomite during fresh-water flow related to Miocene faulting. The long dimension of photograph is 2.2 mm. Cross-polarized light. Sabinal core, sample from 403 feet.

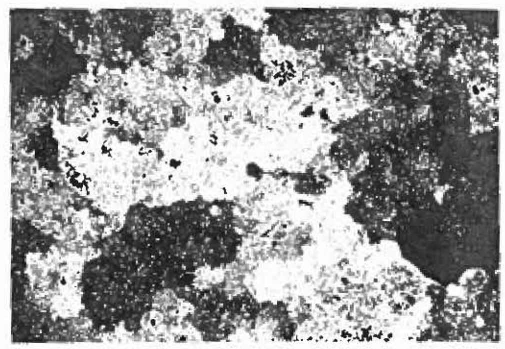

Figure 11. A thin-section photomicrograph of a typical, "luster-mottled" or pseudometamorphic dedolomite. This common type of dedolomite consists of poikilotopic crystals of calcite enclosing and replacing rhombs of dolomite. The calcite is coarse-grained with interlocking crystals. The dolomitic rhombs have corroded edges where they have been partly replaced by calcite. The long dimension of photograph is 6.25 mm. Cross-polarized light. Core TD-3, sample from 424.5 feet.

Luster-mottled dedolomites are mosaics of calcitic crystals coarser than the original dolomite crystals. With time the edges of the dolomite rhombs are attacked and replaced by the calcite. Eventually the whole rhomb may be replaced. The resulting dedolomite is luster-mottled with relict, 10 to 100 micron dolomitic crystals poikilotopically enclosed in large crystals of calcite (Figure 11). Centers of crystals may be subjected to calcitization first because they were originally a less stable form of dolomite (Ellis, 1985). In some dedolomites of this type, allochems are well preserved but in others allochem outlines are completely obliterated. The

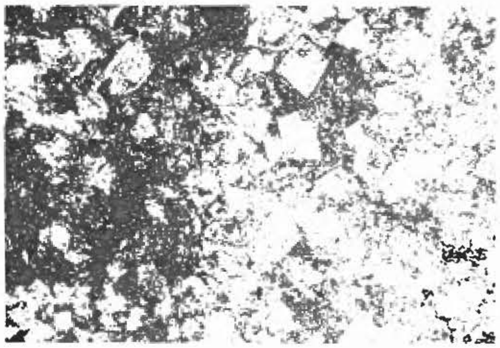

Figure 12. This is a common type of dedolomite in which the centers of dolomite rhombs have been leached and later refilled with single crystals of calcite. Some of the rhombs in this photograph are still hollow. Intercrystalline porosity has been filled with calcite at the same time that many of the hollow, dolomitic rhombs were filled. The long dimension of photograph is 0.77 mm. Plane-polarized light. Selma core, sample from 659 feet.

luster-mottled or pseudometamorphic type of dedolomite is the most common type in the Edwards.

Figure 12 shows leached dolomite rhombs whose centers have been filled with calcite (although some rhombs in this photograph are still hollow). The calcite centers in these rhombs are single crystals in near crystallographic continuity with the dolomite. Intercrystalline porosity has been filled with calcite at the same time. Calcite may be replacing dolomite with more calcian or inclusion-rich centers, interpreted as having formed in a schizohaline environment. In these dedolomites, a distinct void space formed before precipitation of calcite.

Geochemistry of dedolomites

Dedolomitization is a result of reactions between the Edwards dolomitic matrix and groundwater in the aquifer system formed as a result of Miocene faulting. Isotopic compositions of the dedolomites are set by these reactions. Concentrations of ^{18}O and ^{13}C are both low, and their values vary roughly inversely, whereas those of the dolomites and early calcites vary together (Figure 3). Isotopic values for the dedolomites follow a similar trend to those of the microspars and pseudospars. As with the microspars and pseudospars, it can be shown that dedolomites are in isotopic equilibrium with Edwards water on a regional scale, which supports the contention that the dedolomites are forming from present-day formation-water (Pearson and others, manuscript in prep.).

Edwards waters causing dedolomitization were enriched, but undersaturated, in dissolved $CaSO_4$ and have a low Mg^{+2}/Ca^{+2} ratio (Pearson and Rettman, 1976). These pore fluids dissolved gypsum and dolomite. The fluids which dissolved the sulfate in the Edwards Group were of meteoric origin and the dissolution of $CaSO_4$ made them chemically quite active with respect to the associated carbonate minerals. The solution then became supersaturated with respect to $CaCO_3$ and precipitated calcite. The addition of Ca^{+2} to the water lowered the Mg/Ca ratio sufficiently to dedolomitize (a ratio of much less than 1:1 according to Folk and Land, 1975) and may have raised the $CaCO_3$ solubility product (as suggested by Mercado and Billings (1975)) sufficiently to help produce radical neomorphism in associated $CaCO_3$ sediments and rocks (Pearson and others, manuscript in prep.).

Causes of dedolomitization in the Edwards Group and timing of formation

Dedolomite in the Edwards Aquifer is not directly related to recent weathering on the outcrop since cores were used in this study. Neither is it related to buried unconformities. Rocks in both the fresh-water and bad-water zones were deposited in similar environments and underwent the same diagenetic history until the establishment of the fresh-water zone in the Miocene. If dedolomite was related to subaerial exposure prior to the Miocene it would have formed in both zones since erosion surfaces are found in both zones. Furthermore, dedolomite occurs throughout the entire 100-200 meter thickness of the fresh-water zone in the cores studied. It is not concentrated in a few zones as would be expected if it formed during subaerial exposure.

The several types of dedolomite in the fresh-water zone are all believed to have formed by the same general mechanism. Extensive, fresh-water flushing moved relict, Mg-rich brines from the fresh-water zone while bringing in abundant Ca^{+2} ions from the limestones in the recharge area. This flushing combined with the dissolution of gypsum in the fresh-water zone to raise the Ca/Mg ratio of the pore waters. The high Ca/Mg ratio and relatively rapid, fresh-water flushing caused calcite to replace dolomite. The abundance of dedolomite in the fresh-water zone and its paucity in the bad-water zone indicates that dedolomitization occurred after the fresh-water aquifer system was established in the Miocene.

Late, Sparry Calcite Cement

Description and Distribution

Many grainstones in the bad-water zone are very porous. Some have been partially dolomitized. Others are cemented with equant or bladed, sparry calcite; these apparently were cemented early in diagenesis in a fresh-water, phreatic environment

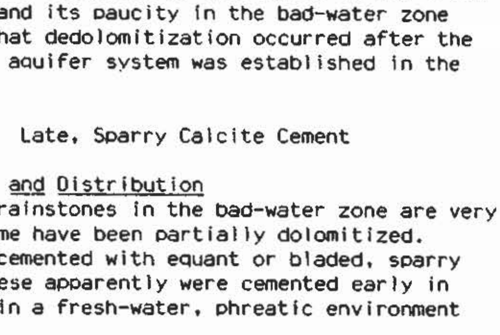

Figure 13. A moldic grainstone with Miocene early meteoric, phreatic cement outside of micritic rims, and rhombic, calcitic crystals which formed later, both inside and outside of the micritic rims. Much moldic and interparticle porosity remains in this sample. The long dimension of photograph is 0.77 mm. Plane-polarized light. Core DX-2, sample from 304 feet.

before the bad-water zone became established, or may have been cemented in the subsurface by Mg-poor, subsurficial waters (Folk, 1974). In the fresh-water zone, equant, calcitic cement is ubiquitous. This biased distribution of sparry calcite is clearly the result of differential cementation by fresh water late in diagenesis after the establishment of the fresh-water zone (Longman and Mench, 1978a).

This cement is most commonly found filling tectonic fractures or lining fracture surfaces and obviously formed as a late cement. In general, fractures in the cores examined from the bad-water zone are closed or tight, whereas fractures in the cores from the fresh-water zone are wider, less cemented, and commonly enlarged by solution. The fresh-water zone contains many vugs that have been partially filled or filled with coarse crystalline calcite. Some of these pore-lining crystals show little evidence of dissolution, whereas others have been corroded by fresh-water flow. Analyses of Pearson and Rettman (1976) show that, in general, waters of the fresh-water zone are saturated with respect to calcite, but a number of wells have waters slightly undersaturated, which could have caused the dissolution of calcite seen in the cores. Several limestone beds in the fresh-water zone are cemented by rhombic calcite (Figure 13). These rhombs resemble dolomite in thin-section but are stained by Alizarin Red S. When examined under the SEM, calcitic rhombs differ from dolomitic rhombs in appearing slightly bloated, i.e. they have more rounded edges and less regular crystal faces. Similar rhombic calcite has been described by Perkins (1968) from rocks of a wide variety of ages and locations. Bebout and others (1977) reported rhombic calcite as a late stage cement in rocks from the Stuart City trend. Folk (1974) suggests that this type of calcite forms in fluids with a low salinity and a low Mg/Ca ratio.

<u>Isotope Geochemistry of Late, Sparry Calcite Cements</u>

Isotopic evidence obtained for late sparry calcitic cements shows that these cements formed under distinctly different chemical conditions than did earlier cements. Results of isotopic analysis of late calcitic cements and travertines can be found in Figure 3. Late calcitic cements and travertines, which can be separated regionally and petrographically from earlier calcitic cements, formed after faulting and result from reactions between earlier cements and dolomites and fresh water introduced after faulting. These reactions can be written generally as:

Fresh water + Dolomite + Gypsum $\rightarrow$
Brackish Water + Calcite
(Mench and others, 1980)

The calcites produced by this reaction are distinct isotopically and texturally from earlier formed calcites. Late calcites have the lowest values of both $\delta^{13}C$ and $\delta^{18}O$, and these values vary inversely, whereas those of earlier calcitic cements and dolomites vary together. These are as light as -7.5°/oo $\delta^{13}C$ and -10.0°/oo $\delta^{18}O$. The carbonate fraction of these is considerably lighter than for the earlier calcites because the former calcites grew in equilibrium with meteoric water containing some organically derived carbon. There is good agreement between isotopic values measured for these late calcites and values predicted based on present-day water chemistry and various temperatures of formation. Data support the hypothesis that the late calcites are forming from present-day Edwards Aquifer water (Pearson and others, manuscript in prep.).

DIAGENETIC MODEL FOR THE EDWARDS

The diagenetic history of Edwards carbonates reflects a number of different diagenetic environments. Early stages of diagenesis began in the marine environment, the site of original formation and deposition of allochems. Later, most sediments were subaerially exposed. Most Cretaceous diagenesis occurred in the meteoric and mixing-zone environments, where a head of meteoric water developed on islands or along prograding shorelines. At the end of Edwards Group deposition, a broad, regionally exposed surface developed, and a meteoric system developed on a more regional scale. Following the formation of the post-Edwards surface, as sea level rose, the Edwards Group was buried by younger sediments, until the Central Texas platform was finally submerged in late Washita time. Major faulting occurred along the Balcones fault zone in the Miocene, which raised the Edwards Limestone in the north and west relative to sea level. Because of the faulting, conditions favorable for producing a circulating fresh-water aquifer developed on the upthrown side of the fault zone. It was the formation of this circulating groundwater system that created the last major diagenetic system that produced marked changes in the petrology of the Edwards Group carbonates.

The initial stages of diagenesis took place in the marine environment with solutions of normal marine chemistry. Major diagenetic features include the formation of micritic envelopes and a minor amount of cementation in the marine environment. Early crusts of bladed cements, probably composed of Mg-calcite, are rare in the Edwards Group within the study area.

The second stage of diagenesis was a local meteoric stage which involved solutions of low Mg/Ca ratios, together with mixing-zone stage, in which Mg/Ca ratios are high but salinities are variable. Evidence indicates that most meteoric diagenesis occurred in the phreatic zone. This early diagenetic stage is the result of the development of fresh-water lenses below islands, or fresh-water tables beneath tidal flats. Diagenetic events in this environment included neomorphism of micrite and grains, including stabilization of Mg-calcite, limited inversion of aragonitic allochems, and extensive dissolution of aragonitic allochems. Minor amounts of syntaxial cements formed on echinodermal fragments, but the dominant form of cement consists of isopachous, bladed to equant, calcitic rims. Hypersaline dolomite formed in supratidal sabkhas. The schizohaline mixing-zone environment, between meteoric and marine environments, produced overgrowths on hypersaline nuclei of dolomite. The formation of gypsum occurred in sabkhas, penecontemporaneous with early formation of dolomite. Silicification occurred after dissolution of aragonite, since no originally aragonitic allochems appear to have been silicified, and silica is a common pore-filling in molds of aragonitic fossils. Silica nodules formed after the formation of some dolomite.

The third stage of diagenesis was the late regional phreatic stage during which a regional meteoric groundwater system developed. This stage probably occurred after the exposure at the end of Edwards Group deposition. This was probably a shallow system of circulation. A deeper system of circulation could not develop until after development of the fault scarp. Coarse, equant calcite filled or partially filled pores remaining after cementation by earlier, isopachous, rim cements. Mixing-zone dolomitization as well as further silicification may still have been occurring during this stage. During this stage, Mg/Ca ratios were variable but the water was normally oxidizing.

A fourth stage of diagenesis occurred in rocks of the fresh-water zone, which developed after major Miocene faulting along the Balcones fault zone raised the Edwards Group on the north and west relative to sea level. As a result of the faulting a circulating fresh-water aquifer system developed on the upthrown side of the fault zone. Extensive neomorphism of micrite to microspar and pseudospar has occurred in the fresh-water zone following development of a circulating, fresh-water system. Coalescive neomorphism of micrite is common throughout all cores of the fresh-water zone, whereas it does not exist in cores of the bad-water zone. Another type of neomorphism of micrite to microspar and pseudospar in the fresh-water zone is related to red clays introduced into the formation. Red clays are most common in the fresh-water zone in cores located nearest the axis of the San Marcos arch. The area of the San Marcos arch began to rise in early Washita time, causing erosion on the surface of the Edwards Group in this area (Rose, 1972). The San Marcos arch area was later subjected to greatest fault displacement during the Miocene (Woodruff and Abbott, 1979). The joints and faults superimposed additional avenues for the development of porosity and permeability into an area that already had considerable secondary porosity. Porosity continued to develop during the Tertiary and Quaternary, and terra rossa entered the openings thus created in the middle and late Pleistocene. Paleontologic evidence suggests that the clays are younger than Pliocene, which suggests that the microspar associated with these clays formed during the Pleistocene or Holocene.

Another major diagenetic change subsequent to formation of the fresh-water zone is extensive dedolomitization of rocks in the aquifer. Edwards waters causing dedolomitization had a high Ca/Mg ratio. These pore fluids dissolved gypsum and dolomite. The solution, supersaturated with respect to $CaCO_3$, precipitated calcite. Thus the dissolution of gypsum and dolomite and the precipitation of calcite occurred simultaneously.

Late, sparry calcite cements are another diagenetic product in the fresh-water zone, and were a result of differential cementation by fresh water. These late calcitic cements include fracture-filling calcite, travertine, and vug-cementing calcite. In addition, rhombic calcite has been found to be a late stage cement in several cores. Late calcitic cements are distinct isotopically and texturally from earlier calcites. The data support the hypothesis that the late calcites are still forming from present-day Edwards Aquifer water. Diagenetic pathways of calcites and dolomites are shown in Figure 14, along with approximate present-day compositions of fresh-water zone and bad-water zone waters.

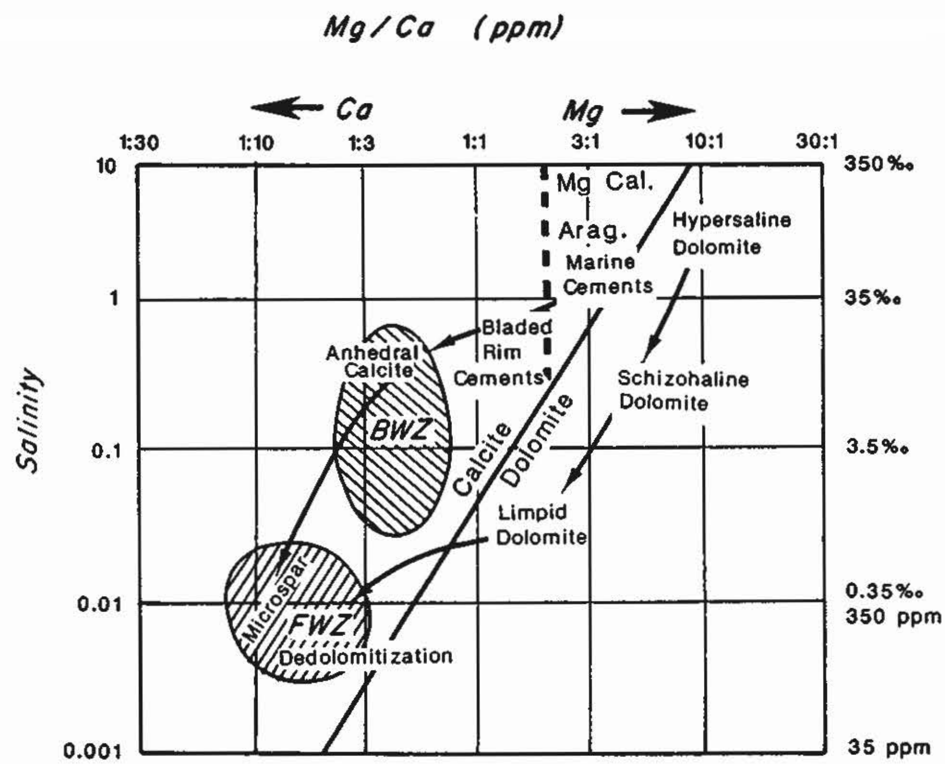

Figure 14. Fields of occurrence of diagenetic products plotted on a graph of salinity versus Mg/Ca ratio (modified from Folk and Land, 1975). Postulated common diagenetic pathways of calcites and dolomites in Edwards Group carbonates are shown. Also shown are the present-day compositions of waters of the fresh-water zone and bad-water zones (hatchured areas).

This study of the relationships between diagenesis and interstitial fluids in the Edwards Aquifer has demonstrated the profound effects that changes in pore-fluid chemistry have on diagenesis in shallow-subsurface environments. The carbonate rocks of the Edwards Group had already reached a so-called "stable" mineralogy of calcite and dolomite when the circulating fresh-water aquifer developed. In spite of this, considerable additional diagenesis occurred in the fresh-water zone.

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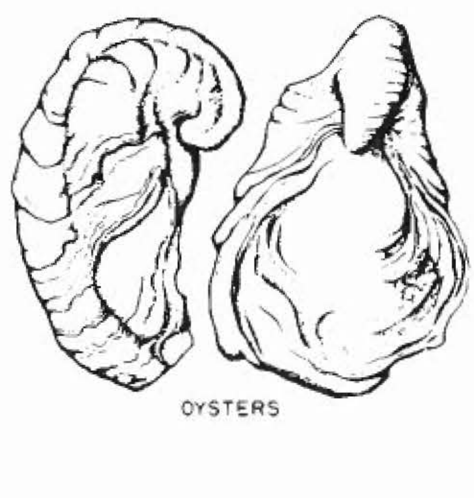

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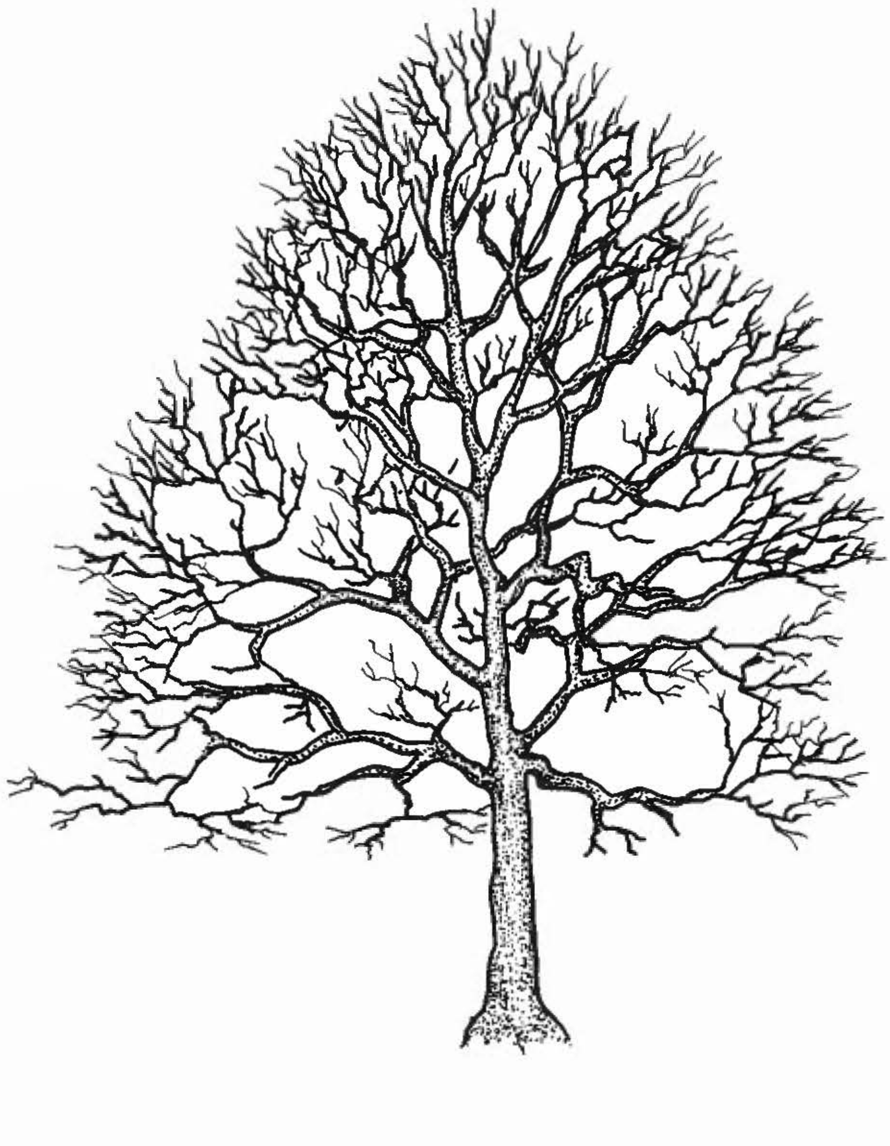

HYDROCHEMISTRY OF THE COMAL, HUECO, AND SAN MARCOS SPRINGS, EDWARDS AQUIFER, TEXAS

Albert E. Ogden, Ray A. Quick and Samuel R. Rothermel
Edwards Aquifer Research and Data Center
Southwest Texas State University
San Marcos, Texas 78666

ABSTRACT

The hydrochemistry of three of the largest springs emerging from the Edwards Aquifer was analyzed weekly for a year period to determine if locally derived recharge could be enhanced through dam construction as a means of preserving spring flow. A recent model has predicted the cessation of spring flow to occur as early as the year 2020 due to Edwards Aquifer ground-water mining around San Antonio. This model did not consider the possibility of separate flow systems to the various spring orifices. Two recent tracer tests have verified differing flow patterns to the San Marcos Springs. Also, the hydrochemical analyses of six San Marcos spring orifices has demonstrated that two chemically different spring groups exist. The southern group of orifices display higher temperature, tritium, and dissolved oxygen concentrations when compared to the northern group of spring orifices. Also, changes in discharge have a more profound effect on water chemistry for the northern spring orifices.

A detailed potentiometric surface map was constructed around San Marcos during low spring-flow conditions (70 cfs, 2 cms). The highly fractured and faulted Edwards Limestone produced a very complex potentiometric surface configuration. The numerous faults associated with the Balcones fault zone can act as either ground-water barriers or avenues of enhanced ground-water flow. Pressure head distributions demonstrate the existence of two separate flow regimes: one of "older" water from the San Antonio region, and the other of "younger" water moving to the springs from the Blanco River. The potentiometric surface map and one dye trace also demonstrate that the Blanco River is losing water to the Edwards Aquifer through highly fractured rock in the river bottom, directly recharging the San Marcos Springs. Therefore, by devising ways of artificial recharge, either by drilling holes in the river bottom or by diverting river water to bedrock sinkholes along the river banks, or by constructing a dam, up to 80,000 acre-ft/year ($9.87 \times 10m^3$/year) of enhanced recharge water could be contributed to the aquifer to maintain the flow of the San Marcos Springs.

Hueco Springs is composed of recent, locally-derived recharge water as demonstrated by dye trace results, turbidity, and rapid fluctuations in water chemistry after storms. The flow of Hueco Springs could be enhanced by placing a recharge dam on Elm or Blieders creek.

Some locally derived recharge waters reach Comal Springs as evidenced by chemical changes following storms. These changes are not large or long lasting. Also, all attempted dye traces failed to reach the springs. Tritium values are low. Water-chemistry changes are gradual and are related to longer term seasonal and discharge effects. Therefore, a local recharge dam would not enhance spring flow. San Antonio utilizes water levels in a reference well to determine when rationing must begin. To save Comal Springs, the chosen level for mandatory rationing must be increased to approximately 625 feet (above sea level).

INTRODUCTION

The Edwards Limestone is a complexly fractured and faulted, designated sole-source aquifer that provides the water needs for nearly two million people, including the city of San Antonio. Rapid urban development has increased the chances of contamination and has caused the average pumpage rate to now nearly equal the average yearly recharge rate of 595,000 acre-feet ($7.34 \times 10m^3$ /year). The most significant natural discharge points for the aquifer are three of the largest springs in Texas, the Comal, Hueco, and San Marcos springs (Figure 1). These springs are major recreational areas for central Texas and contain several rare and endangered plant and animal species. Comal Springs ceased to flow during the drought of the mid 1950's and the drought of 1984. The San Marcos Springs continued to flow but reached a record low of 46 cfs (1.3 cms) in 1956

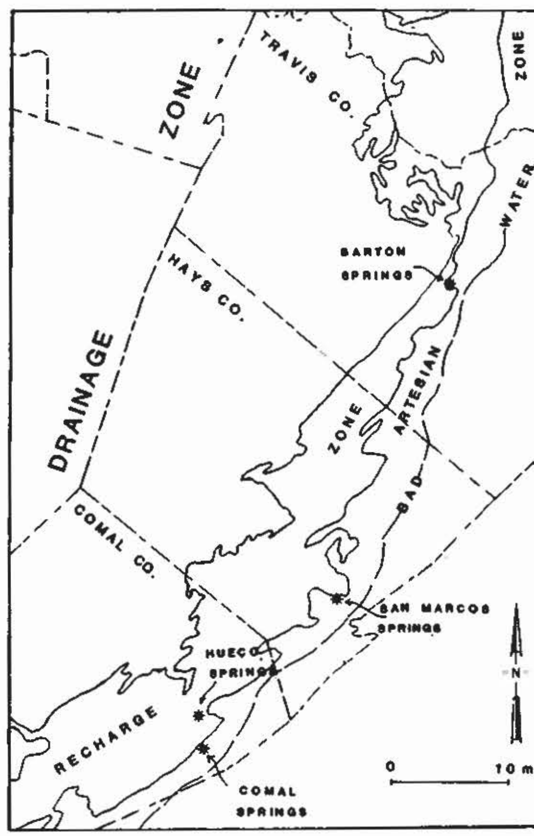

Figure 1. Location of Barton, San Marcos, Hueco and Comal springs.

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and 60 cfs (1.7 cms) in 1984. Tritium studies of the Comal Springs by Pearson et al. (1975) and time series analysis of fifteen water chemistry parameters by Rothermel and Ogden (1986) have demonstrated that the various Comal Spring orifices receive very little local recharge except during high water table conditions. In contrast, early tritium measurements of the San Marcos Springs, suggested that the these springs receive a mixture of old and recent recharge (Pearson et al., 1975). Hueco Springs has the highest tritium content and is believed to be composed of very recent ground water.

Recent studies by Espey et al. (1975), Klemt et al. (1975), and Guyton and Associates (1979) have led to modeling predictions that suggest discharge from all three springs could cease by the year 2020 due primarily to ground-water mining in the San Antonio area. This hypothesis was based on uniform, homogeneous flow to the major orifices of the springs. For San Marcos Springs, samples taken by Pearson et al. (1975) were only from one orifice since the others are below the lake's surface (Figure 2). Preliminary sampling of each of the San Marcos Springs orifices by divers (Ogden et al., 1986) showed that based on water chemistry, two seemingly hydrologically separate spring groups exist. If this hypothesis could be substantiated, then the predictions of the model could be wrong, and some method of preserving spring flow might be found. Therefore, the objective of the research was to utilize ground-water tracers and spring-water chemistry to determine if separate flow regimes actually exist at the San Marcos Springs, and if a similar situation occurs at Hueco or Comal Springs.

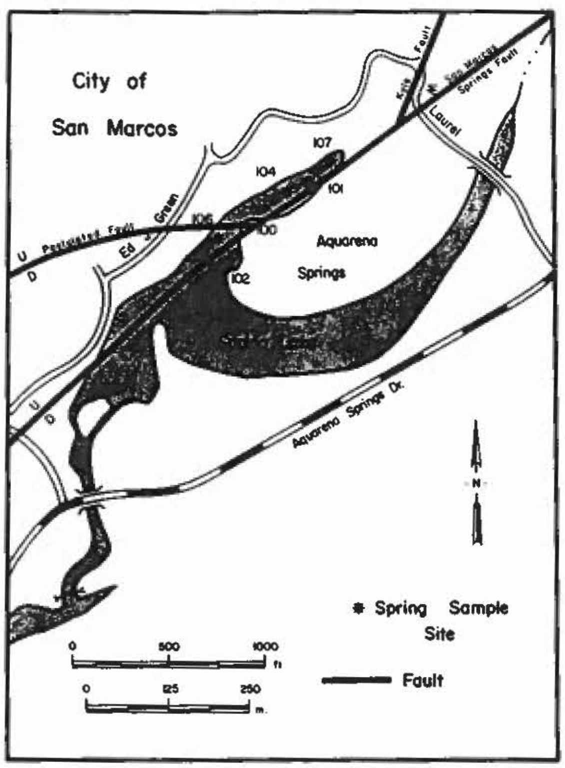

Figure 2. Major orifices of the San Marcos Springs (Divergent, 100; Cabomba, 101; Deep, 102; Johnny, 104; Catfish, 106; Hotel, 107).

LOCATION, PHYSIOGRAPHY, AND GEOLOGY OF THE STUDY AREA

The study area is located along the Balcones fault escarpment in Hays and Comal counties, Texas. The study area lies between two major physiographic provinces of the southwestern United States; the Edwards Plateau and the Gulf Coastal Plain. The topographic expression that forms the dividing line for the provinces is the Balcones Escarpment. West of the escarpment is the karstic Edwards Plateau. The area immediately east of the escarpment is the Blackland Prairie of the Gulf Coastal Plain.

The Edwards Aquifer is composed of a group of Cretaceous carbonates that have a total thickness of approximately 450 feet (137 m) in the San Marcos area. The Edwards Aquifer is composed of the Comanche Peak Limestone, Edwards Limestone, and Georgetown Limestone. Rose (1972) raised the Edwards Limestone to group status in central Texas and divided it into the Kainer (lower) and Person (upper) members. The Edwards Aquifer was later divided into hydrostratigraphic units by Maclay and Small (1983) through a detailed analysis of cores and geophysical logs. Lithologically, the Edwards Aquifer consists of rudist limestones; burrowed tidal-flat wackestones, grainstones, dolomite, nodular chert, solution-collapse breccias, and weathered, honeycombed beds.

Recharge to the aquifer occurs through losing streams located primarily to the west and south of San Marcos and New Braunfels. Surface water moves across the impermeable rocks of the Glen Rose Formation until (drainage zone, Figure 1) the Edwards Aquifer is encountered at the Balcones fault zone. Most of this water moves in a general east/northeast direction where it discharges at the Comal, Hueco, and San Marcos springs. Complex "down to coast" faulting causes the Edwards Aquifer to lie deeper and deeper below the surface as one transects in a southeast direction. Where the aquifer is exposed at the surface, it is termed the recharge zone. Where the Edwards is completely saturated and buried beneath the impermeable Del Rio Clay and younger rocks, it is termed the artesian zone. The bad water line represents the eastern edge of the aquifer where poor circulation has caused the water to have a high TDS (>1000 mg/l) and be non-potable.

The San Marcos Springs are the second largest spring group in Texas with a mean history flow of 161 cfs (4.50 m^3/sec). They are located in the city of San Marcos in Hays County and are owned and operated as a tourist attraction by Aquarena Springs, Inc. The spring orifices are now under up to 40 feet of water due to a dam originally created for hydroelectric power. Water issues from six major orifices along the base of the Balcones Escarpment (Figure 2) as well as from numerous smaller openings; some are marked by sand boils. Samples from the six orifices were retrieved by divers. A temperature/dissolved oxygen (D.O.) probe was placed at each orifice during sampling and read from above by researchers in a glass-bottomed boat. The elevation of the lake surface is 574 feet (175 m) above sea level.

Comal Springs is the largest spring group in Texas with a mean historic flow of approximately 300 cfs (8.31 m^3/sec). This average has been decreasing in recent years as water-well withdrawals around San Antonio have increased. The springs are located in New Braunfels, Comal County and issue from four major orifices above the lake surface (Figure 3). These orifices are located along a 1500 yard (372 m) stretch of the base of the Balcones Escarpment. The spring openings are at about 623 (190 m) feet above sea level. The lake is presently used for recreation and the production of hydroelectric power.

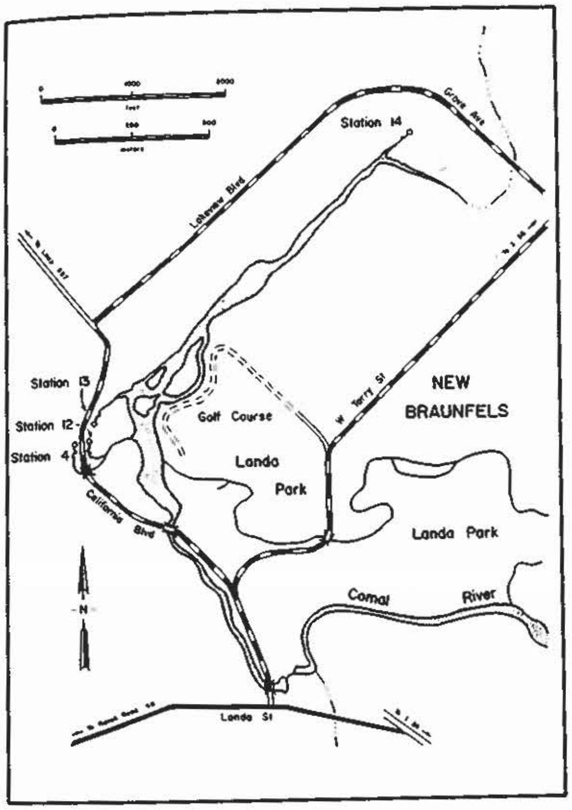

Figure 3. Location of Sampled orifices of Comal Springs.

Hueco Springs is located three miles north of New Braunfels and is composed of two major orifices in limestone covered by Quaternary alluvium 300 feet west of the Guadalupe River (Figure 4). The altitude of the springs orifices are 658 ft (201 m) and 652 ft (199 m) above sea level. Spring flow is very variable and historically has not been measured as often as the Comal and San Marcos springs. The Hueco Springs commonly cease to flow during droughts. The maximum recorded discharge was 131 cfs (3.71 m^3/s) in 1968 (Guyton and Assoc., 1979).

TRACER TESTS

Two ground-water tracer tests were performed to aid in interpreting flow directions and velocities to the San Marcos Springs. The first test was conducted in Ezell's Cave, located on the San Marcos Springs fault (Figure 5). Two pounds (0.90 kg) of sodium-fluorescein green dye were

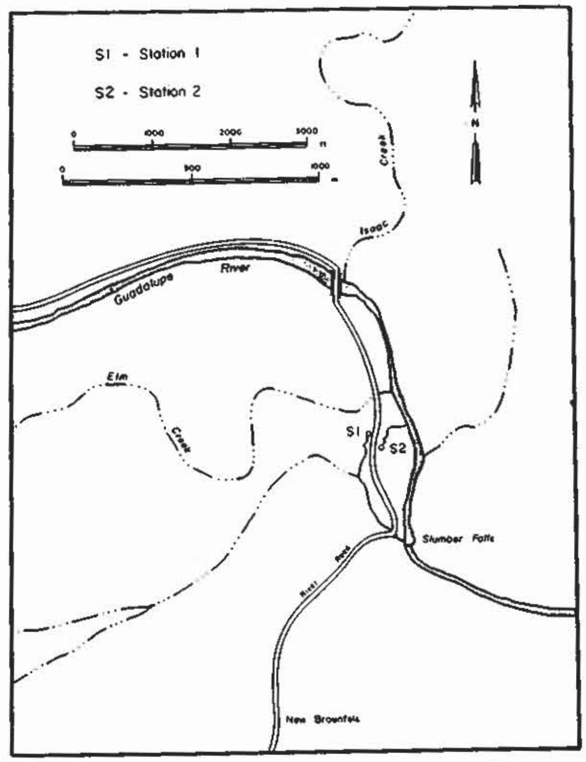

Figure 4. Location of Hueco Springs sampling sites, Comal County, Texas.

placed in the Ezell's Cave lake during a period of average (approximately 140 cfs (4 cms)) spring discharge. Prior to the test, charcoal packets for dye absorption were placed at six spring orifices and two wells. The dye was detected within nine days at the Southwest Texas State University artesian well and on the 10th day at one of the City's wells. Charcoal traps were retrieved from the San Marcos Springs by divers 11 days after dye injection and surprisingly only one orifice (102-Deep Spring, Figure 2) was positive. The velocity of travel was approximately 1500 ft/day (457 m/day). Nearly 30 days later, dye also emerged from the Catfish Spring orifice (106) of the San Marcos Springs. Continued monitoring of the spring orifices showed no presence of dye from any other spring orifice. The tracing experiment was repeated about six months later and the results were the same. A fault was mapped by Guyton and Associates (1979) which separates the southern set of spring orifices (Deep and Catfish) from the northern set (100-Divergent, 104-Johnny, 101-Cabomba, and 107-Hotel, Figure 2). This fault could have sufficient displacement to act as a ground-water barrier. The fact that it took approximately 30 days to move only 230 feet (70 m) between the Deep and Catfish spring orifices, suggests minimal hydrologic connection and/or a zone of extremely slow ground-water movement possibly caused by a meeting of two separate pressure systems.

A second trace was conducted from a lake in Rattlesnake Cave during low flow conditions of the San Marcos Springs (60 cfs, 1.7 cms). Three ounces (86 grams) of sodium-fluorescein dye and five pounds (2.3 kilograms) of Tinopal CBS-X, an optical brightener, were utilized. Rattlesnake Cave is

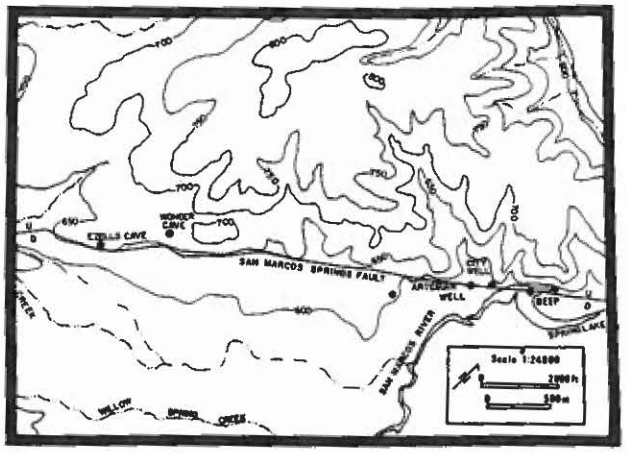

Figure 5. Flow paths of tracer tests performed by Ogden (1983) and Quick and Ogden (1985).

located approximately 4000 ft (1220 m) northeast from the head of Spring Lake (Figure 5). In eleven days the dye was detected at Sink Spring and a well approximately 500 feet (153 m) southwest of the cave. Finally, 40 days after the test began, the dye emerged from all six monitored orifices of the San Marcos Springs. The slower velocity of transport may be attributed to low spring discharge and the extremely flat water table conditions brought about by the eight month drought. The emergence of the dye from all spring orifices suggests that the fault boundary crossing Spring Lake also may act as a pressure-head boundary allowing reversals of flow directions during differing flow conditions. Another possibility is that water moving southwest from the Sink Creek drainage basin may bifurcate in a down-gradient direction; whereas, the water moving in a northeast direction along the San Marcos Springs fault may stay confined within a narrow pathway.

Five ground-water traces were performed around Comal Springs, but none of the dyes appeared at any of the spring orifices. This supports earlier hypotheses that very little recent, locally derived recharge waters emerge from Comal Springs (Pearson et al., 1975). Rettman (pers. comm., 1984) once injected dye into a well in Panther Creek about 500 feet (155 m) from the nearest spring orifice (Comal 1). Surprisingly, the dye emerged only from the Comal 3 orifice. The trace was repeated, and the results were the same. This demonstrates that at least some separate flow paths feed the individual spring orifices. Whether these limestone conduits are interconnected at some distance from the springs and merely bifurcate near the springs is unknown. Quinlan and Rowe (1977) have discovered similar bifurcation in some Kentucky springs documented by actual cavern explorations.

One successful trace was made to Hueco Springs. A pound (2.2 kg) of fluorescein dye was injected about two miles (3.2 km) southwest of Hueco Springs (Figure 6). Within five days, the dye detectors tested positive, indicating that recent storm waters contribute significantly to the discharge of the springs. The charcoal absorption packets were not tested until five days after dye injection, so the travel time may have been significantly less.

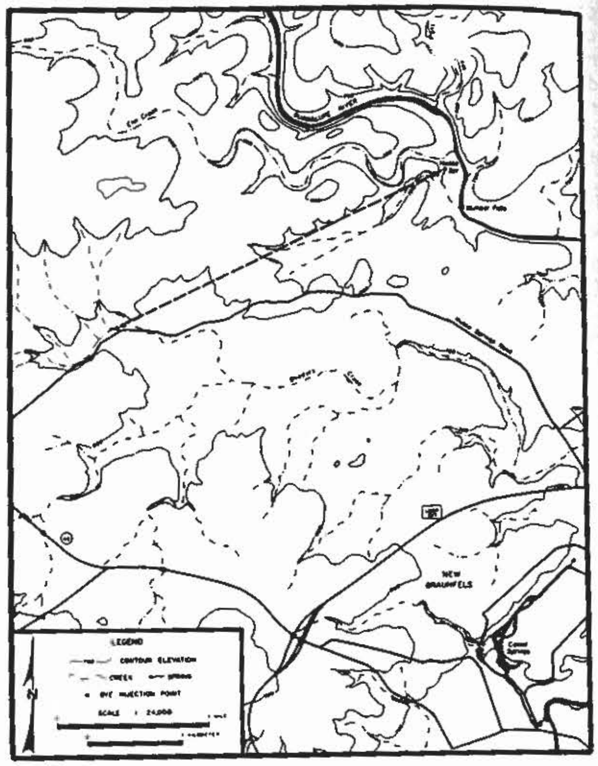

Figure 6. Dye-trace to Hueco Springs.

POTENTIOMETRIC MAP

The first potentiometric map of the Edwards Aquifer in the San Marcos area was drawn by DeCook (1956). He utilized only 13 wells for the Edwards Aquifer in Hays County. His map failed to show the effects of faulting on the water table configuration and suggested no flow to the San Marcos Springs from points to the north/northwest such as the Blanco River. A model of the potentiometric surface map was constructed by Klemt et al. (1975) for the entire aquifer region for the purpose of predicting the time of cessation of flow from the Comal and San Marcos springs. This map was also too generalized for Hays County. Therefore, a detailed potentiometric surface map was needed to determine the effect of faulting on ground-water flow and as a means of distinguishing ground-water flow directions.

A detailed potentiometric surface map was constructed utilizing 75 static water-level measurements within the 50 square mile (130 sq km) study area within a short period of time in October and November of 1984 (Figure 7). Very little water-table elevation change occurred during this time as demonstrated by the monitored static water levels of twelve wells located throughout the study area. The precipitation that occurred during October and November had little effect on the water table elevation. From this, it is evident that significant interconnected cavity porosity exists within the zone of water table fluctuation as is predicted by theories on the evolution of solution cavities.

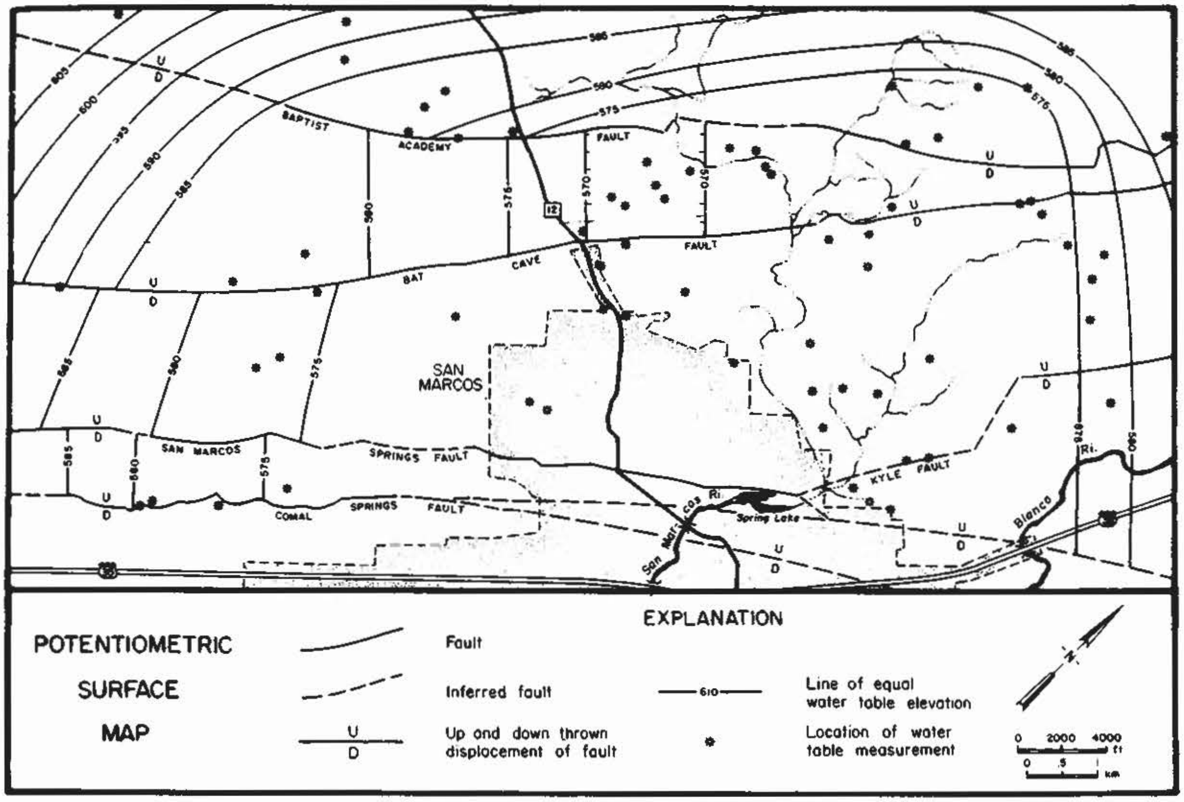

Figure 7. Potentiometric surface map of the San Marcos area.

The configuration of the water table is very complex due to the structural complexity of the study area. There are numerous faults, cross faults, and joints that dissect the San Marcos area and cause ground-water movement to be impeded or enhanced. Only the major faults are shown on the potentiometric surface map. This new potentiometric surface map demonstrates that the movement of ground water has been modified by the Balcones fault zone. Several faults traversing the study area have vertical displacements of 50 to 350 feet (15 to 107 meters). These normal faults form en echelon fault blocks which create, in some places, isolated avenues of ground-water flow and ground-water barriers. Similar fault control of ground-water flow is also seen in Holt's (1956) potentiometric surface map of Medina County, which is also located in the Balcones fault zone. He demonstrated that faults with significant displacement create barriers to ground-water movement and that water will "spill out" into an adjacent fault block where the displacement of the faults decrease.

The potentiometric surface map also suggests that ground water is moving from the San Antonio portion of the aquifer confined between the San Marcos Springs fault and Comal Springs fault. Each of these faults has over 300 feet (90 m) of displacement, and both are believed to form hydrologic barriers to ground-water movement. Some local recharge waters may enter the fault block when Purgatory Creek flows during major storm events. If this local water does enter the fault block, it must be insignificant compared to the amount in storage because no chemical changes of the springs occur after storms.

In the San Marcos area, "local" recharge waters enter the study area from the west and move down-gradient to the southeast. The movement of ground water is then diverted by the Baptist Academy fault (Quick, 1985) because it has significant displacement in the western half of the study area. The displacement of the Baptist Academy and Bat Cave faults decreases in a northeast direction. As a result, ground water is believed to change direction and move towards the south to the San Marcos Springs along fractures and minor cross-faults. The potentiometric map also demonstrates that recharge is occurring from the north/northwest (Sink Creek-Blanco River) to the San Marcos Springs. A recent Blanco River loss study by Watson (1985) has shown that the Blanco River is losing water near the Halifax Ranch (Figure 8) to the Edwards Aquifer in the same area suggested by the equipotential lines. At one point along the losing stretch, a 30 foot (9 m) deep cave (Tarbuttons Showerbath Cave, Figure 8) occurs just 20 feet (6 m) from the river. The cave crosses beneath the river, but less than 1 cfs (0.03 cms)enters the cave as seepage from the roof. A dye trace was performed by Ogden et al. (1985) linking these cave waters to the San Marcos Springs. Watson's (1985) study stated that the annual volumes of recharge by the Blanco River into the aquifer, 1934 to 1977, varied from a high of 85,900 acre-feet (1.06 x $10m^3$/year) in 1975 to a low of 8,200 acre-feet (1.01 x $10m^3$/year) in 1950. The average annual recharge for the 1934 to 1977 period was 36,000 acre-feet (4.44 x $10m^3$/year). If recharge from the Blanco River were to be enhanced, it could provide the means of ensuring continued discharge from the San Marcos Springs.

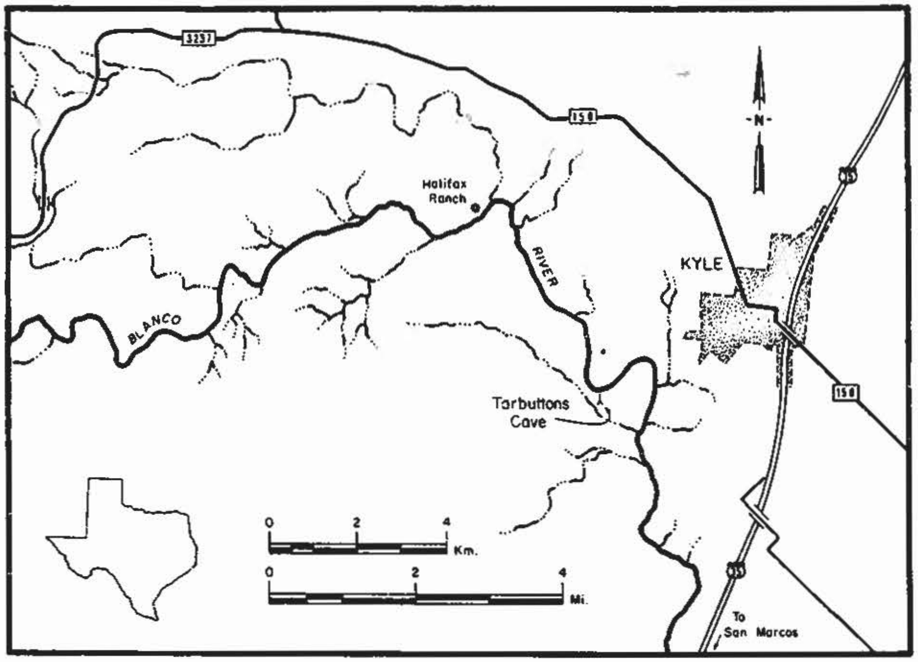

Figure 8. Location of Tarbuttons Cave, the Halifax Ranch, and the Blanco River near Kyle, Texas.

HYDROCHEMISTRY - SAN MARCOS SPRINGS

Six orifices of the San Marcos Springs were sampled by divers at least every two weeks from August, 1982 through July, 1983. During this time, the total discharge of the springs increased from 60 cfs (1.7 cms) to 160 cfs (4.5 cms). Two of the measured parameters, temperature and dissolved oxygen, show distinct differences between the southern and northern group of spring orifices. Figure 9 shows the temperature and discharge data for both the Deep and Johnny spring orifices of the San Marcos Springs. The Deep spring orifice (site #102, Figure 2) was chosen to represent the southern group because of its greater discharge. The Johnny spring orifice (site #104, Figure 2) was chosen to represent the northern spring group because it was spatially in the middle and also had a continuous high discharge rate throughout the study year. Each chosen orifices is statistically representative of its group, based on comparison of means for 15 chemical parameters. It is important to note that discharge was not measured at each individual orifice since they were all under more than 10 feet (3 m) of lake water. The Deep spring orifice has a mean average temperature of 22.3°C. An analysis of variance test, F-probability 0.0001, designates a statistical difference between the two spring orifices at alpha equals 0.05. The temperature of Deep spring is always above 22.0°C and Johnny's is always below 22.0°C. The importance of Deep's higher temperature is that it is warmer than expected for shallow ground water in the Edwards Aquifer. All of the spring orifices of the northern group have an average temperature that is expected for shallow ground water. Hueco Springs, for example, is known to discharge almost entirely shallow ground water at an average temperature of 21.3°C. In areas around San Antonio where the Edwards is over 1500 feet (457 m) below

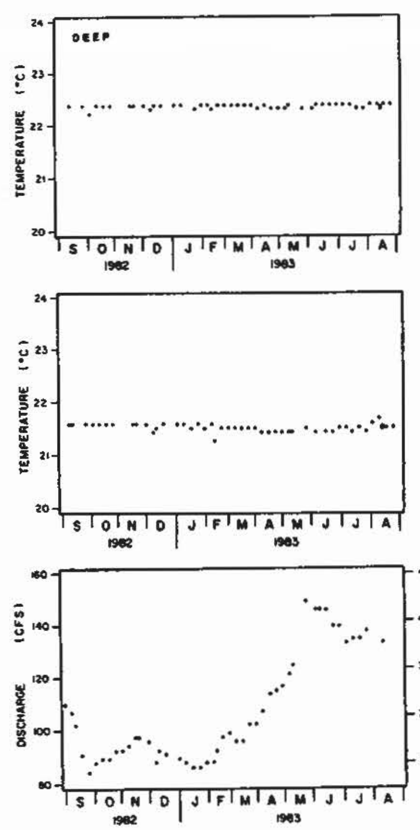

Figure 9. Time series plot of temperature for Deep and Johnny spring orifices compared to total discharge of the San Marcos Springs.

the surface, ground water can be up to 25°C. Comal Springs, which receives little or no local recharge, has a mean average temperature of 23.2°C (Rothermel and Ogden, 1986). As the warm ground water beneath San Antonio moves upwards in its path to the Comal Springs, it is slowly cooled. As the underflow then continues northward to the Deep and Catfish orifices of the San Marcos Springs, it apparently cools another degree.

When the summer and spring rains occurred and discharge increased, the temperature at the Johnny spring orifice decreased, but Deep's did not. This suggests that during drought periods the hypothesized pressure boundary shifts northward and provides some older and warmer water to the northern spring group. Once the total discharge of the San Marcos Springs reaches approximately 100 cfs (2.8 cms), Johnny and the other orifices of the northern spring group then return entirely to younger and cooler local recharge waters, derived primarily from the Blanco River.

Figure 10 displays plots of dissolved oxygen concentration (D.O.) and discharge against time for the Deep and Johnny spring orifices. The average dissolved oxygen content for Deep spring is 5.7 mg/l and Johnny's is 4.1 mg/l. The coefficient of variation for Deep is 5.1% and Johnny's is 9.7%, demonstrating the greater variability of the northern group of springs. The analysis of variance, F-probability of 0.0001, statistically shows a significant difference in dissolved oxygen content between the two orifices at alpha equals 0.05. Most outstanding is that Deep spring nearly always has higher D.O. content than Johnny. This again suggests that two different flow systems converge at the San Marcos Springs.

The average dissolved oxygen concentration of the six spring orifices of the San Marcos Springs gradually increases in a northward direction. Dissolved oxygen displays a negative correlation against discharge for Johnny (alpha equals 0.05) whereas Deep remains relatively unaffected. During low flow periods, Johnny's D.O. approaches that of Deep spring. When the drought ended in October, 1984, spring discharge increased and Johnny's D.O. dropped significantly. This further supports the independent flow regime hypothesis and that this separating boundary moves in response to changes in hydrostatic pressure between the two systems.

Other indicators that support this hypothesis are the calcium hardness and tritium values. Figure 11 shows a plot of calcium hardness and discharge versus time for the two spring orifices. Water emerging from the Deep spring orifice is nearly always harder due to the longer residence time associated with the greater transport distance. Tritium samples were taken in October, 1984 during low flow conditions, but after several storm events took place. The tritium value for Deep spring was 7.1 ± 0.5 and Johnny's was 9.5 ± 0.6 tritium units. Current precipitation has approximately 9 tritium units at the Waco, Texas station. Therefore, the data show that water emerging from the Johnny spring orifice is primarily from recent, local recharge.

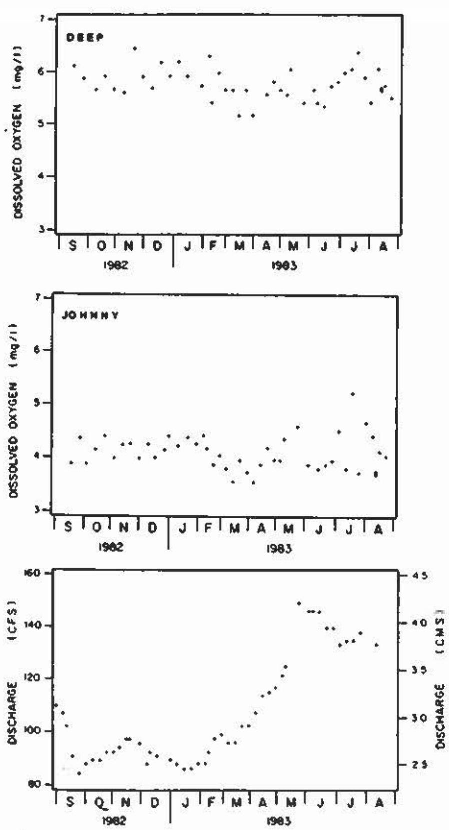

Figure 10. Time series plot of dissolved oxygen concentrations for Deep and Johnny spring orifices compared to total discharge of the San Marcos Springs.

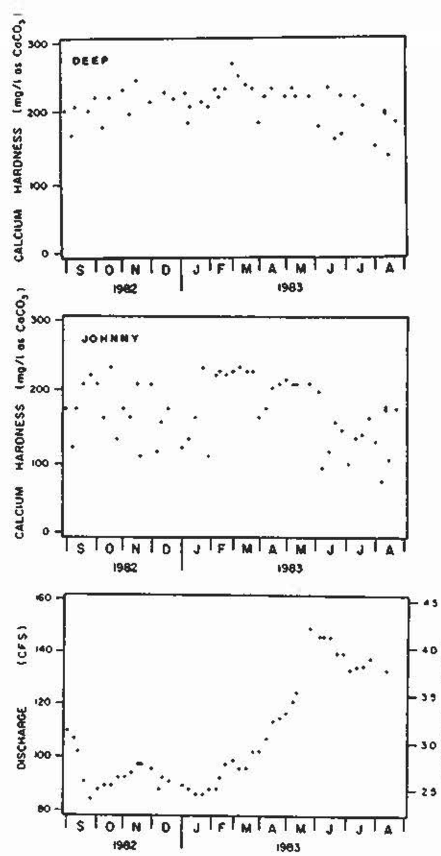

Figure 11. Time series plot of calcium hardness concentrations versus total spring discharge for the Deep and Johnny spring orifices.

HYDROCHEMISTRY - COMAL AND HUECO SPRINGS

Each of the four Comal Spring orifices and two Hueco Spring orifices were sampled weekly for a year period in 1982 and 1983, and during a large storm to determine the effects of season, discharge, and recharge events on spring-water chemistry. One of the objectives of this study was to determine if all spring orifices discharge chemically similar water or if there are separate flow systems such as was demonstrated for the San Marcos Springs. Statistical comparison of the means of 15 chemical parameters showed no significant difference between any two spring orifices for each spring group, but significant differences did occur between Comal and Hueco Springs. Therefore, just the data from the Comal I spring orifice and the Hueco I orifice will be presented. A more in-depth analysis of all spring orifices and parameters can be found in Rothermel and Ogden (1986).

The Comal I orifice is the highest in elevation of the four and had the second highest discharge. The water emerges from a shallow cave in brecciated Edwards Limestone. Numerous samples were taken during three monitored storm events during the year study period. The rain event data are included in the graphs and can usually be discerned by a series of points falling in a vertical column. Hueco I is the lowest in elevation of two Hueco spring orifices and was chosen because Hueco II ceased flowing for several months during the study.

Total hardness and calcium hardness data (Figure 12) for Comal 1 show limited seasonal variation. A low occurred from September to mid-October, 1982, with a subsequent rise, and an apparent leveling off until mid-January, 1983. The hardness values then began to display a slow rise until late March where they even out and begin to show a drop in the late summer. All the Comal Springs displayed this seasonal trend in hardness. The lower fall and winter values for total and calcium hardness, and the rising trend of hardness in the spring, may be caused by rainwater and soil temperatures which affect dissolution kinetics. As seen in Figure 12, the months with lower total and calcium hardness, are also the months with lower discharge. During these low water-table conditions, former wetted surfaces in the Comal flow system may have dried up, leaving calcium precipitate on the conduit walls. Since higher discharges occur in the spring, the conduit flow path would be more full of water and the flow may become more turbulent, thus redissolving the calcium "flakes" in the conduit, and increasing the dissolution of conduit walls. Higher late winter and spring recharge also may force harder water from the springs due to its longer residence time in the system. Trees and shrubs release carbon dioxide into the soil when active, but during the fall and winter months, when trees are dormant, up to three times less carbon dioxide is released by the roots than in the summer months. In addition, micro-organisms in the soil contribute to soil CO_2, and the bacteria, molds, etc. may have lower activity in the winter, thus causing less soil CO_2. Fertilizers also increase CO_2 production in the soil and, of course, there is little fertilization in the winter months. Therefore, less carbon dioxide in the soil in winter months will reduce the dissolution of soil calcite and regolith as the recharge waters percolate to the flow system.

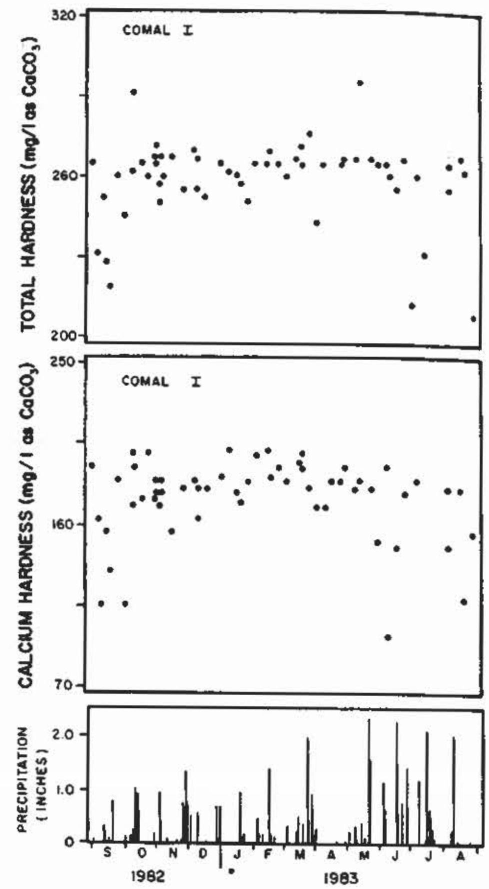

Figure 12. Time series plot of total hardness and calcium hardness concentrations and discharge Comal 1 Spring.

A similar, but better displayed trend is seen on the Hueco Springs plot of total and calcium hardness versus time (Figure 13). Again, note the rain event points which, although they display a definite effect from rainfall, should be ignored to observe the seasonal variations. A very definite increase is seen from fall to late winter for calcium hardness. Although the points are more scattered for total hardness, a rise in the late winter and spring is also observed. An additional control that may cause such a trend is the recharge temperature. It is known that there is an inverse relationship between temperature and calcite solubility. Thus, since cooler recharge occurs in the winter months, more calcium may be dissolved in the shallow vadose zone of the Hueco flow system, increasing the calcium and total hardness of the Hueco ground waters.

All of the Comal Springs have similar and low coefficients of variation (C.V.) for total and calcium hardness indicating that the water has a longer residence time to equilibrate with the limestone and the dolomite. Comal 1 has the lowest C.V. (6.7% for total hardness and 14.7% for calcium hardness), but it has the highest mean and median values, although all the means are close. The plot of hardness against time reflects a better seasonal trend at Comal 3, but the data points are much less scattered at Comal 1. This could indicate that the flow of water initially comes out of Comal 1, then proceeds to flow out of the other three orifices, with a possible mixing of more recent waters (or surface runoff or saturated soil flow from small rains) as it flows along the fault-line to Comal 4, which has the highest C.V. for total (9.4%) and calcium (19.9%) hardness.

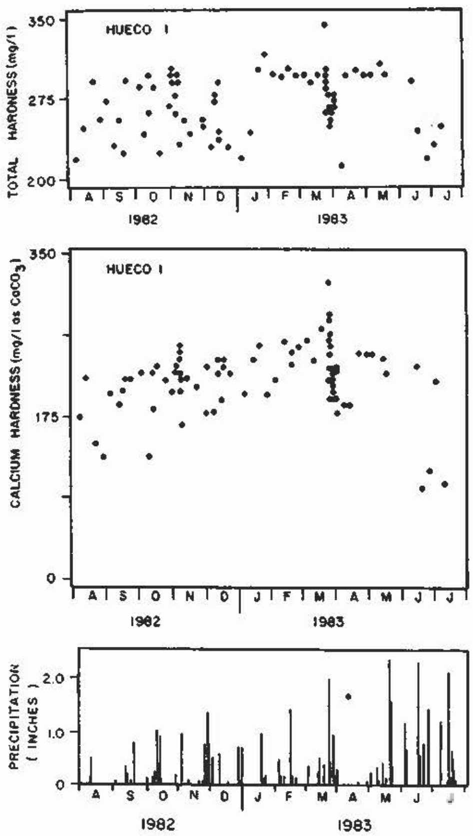

Figure 13. Time series plot of total hardness and calcium hardness concentrations for Hueco I Spring compared to precipitation data.

Hueco I has almost twice the C.V. (11.5%) for total hardness than Comal 1, and the highest mean and median over all the Comal Springs, although Comal 4 has the widest range for total hardness (198 to 340 mg/l as $CaCO_3$). For calcium hardness, Hueco I, again, has a high C.V. (19.2%) and a much higher mean (209 mg/l as $CaCO_3$), median (217 mg/l as $CaCO_3$), and range (178 mg/l as $CaCO_3$) compared to Comal Springs. Additionally, the analyses of variance test (with an F-probability of 0.001) indicates a significant difference between Hueco 1 and the Comal Springs for both total and calcium hardness.

Comal 1 displays a statistically significant (alpha = 0.001) positive or rising trend in calcium hardness as discharge rises. Hueco 1 shows a strong negative (alpha = 0.004) relationship, in contrast. In shallow flow systems where local recharge rapidly moves towards the spring outlet, such as for Hueco 1, calcium hardness is diluted by the rapid influx of lower hardness water. For Comal 1, the increase in discharge is more a reflection of the hydraulic head increase from distance recharge areas.

There are several possible reasons why there is a difference in the hardness concentrations between the Hueco and Comal waters. The higher hardness at Hueco may be related to the turbulent nature of flow allowing more calcium carbonate to be dissolved. The longer flow paths and probable laminar flow for the Comal Springs system may cause calcium carbonate to precipitate in cavities before exiting from the springs. The temperature differences between the springs may also be affecting solution kinetics. Another possibility may be related to the Edwards Group member through which the water primarily flows. It may be that water moves through more soluble, and gypsum-rich beds in the Hueco Spring's drainage basin. It is interesting to note that the calcium hardness of Comal I is significantly less than that for any spring orifice of the San Marcos Springs and that the calcium hardness for Hueco I is closer to that of the Deep springs orifice at San Marcos.

Temperature of the ground water at Comal Springs is very consistent and shows negligible fluctuations with time, although the temperature does appear to rise slightly in the summer months (Figure 14). Temperatures at Comal 1 ranged from 22.0°C (71.6°F) to 23.5°C (74.3°F) during the sampling period, with a C.V. of 1.3%. The scatter that appears on the first part of Figure 14 is due to rain event changes and errors in measurements made with a hand-held thermometer. In January, 1983, temperature measurements were taken with a

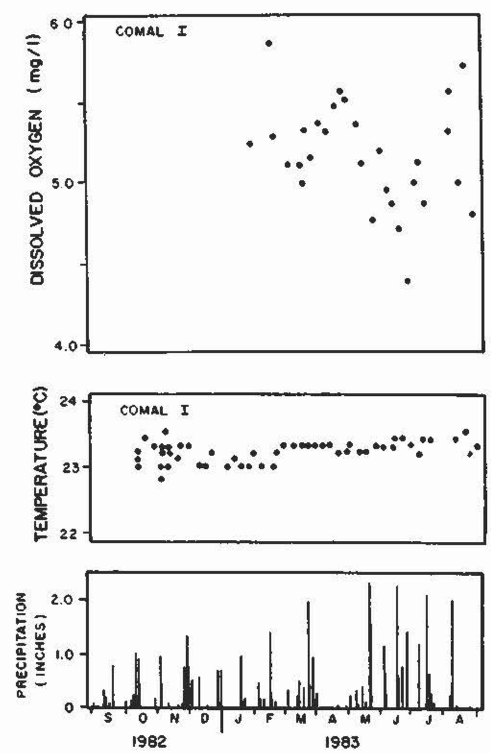

Figure 14. Time series plot of temperature and specific conductance data for Comal 1 Spring compared to discharge data.

YSI digital dissolved oxygen/temperature meter, thus eliminating "eye-balling" error. The change in instruments is well seen in both the Hueco I (Figure 15) and Comal 1 plots. The relatively constant temperature of the Comal waters differs slightly from the mean annual air temperature at New Braunfels (the location of the springs) of 20.6°C (69.08°F). Recharge water which sinks in the western counties of the Edwards Aquifer region migrates to depths of over 2000 ft. before emerging at Comal Springs. Due to this deep circulation, the ground water is heated above the mean annual air temperature.

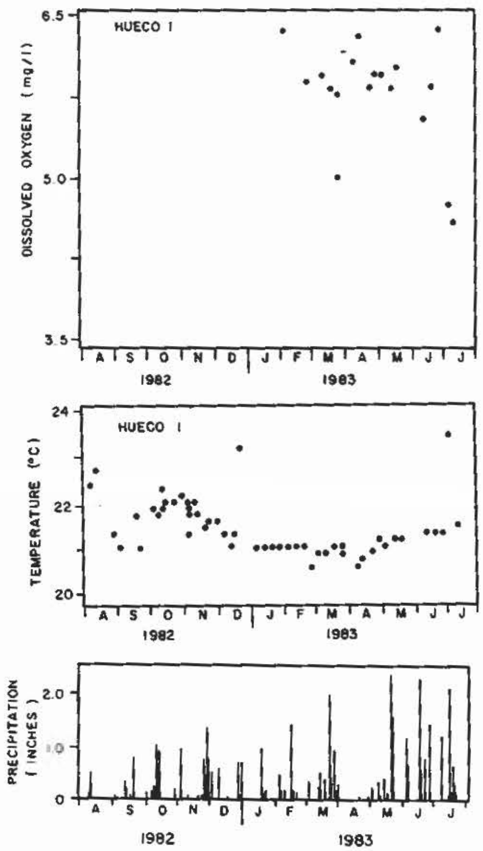

Figure 15. Time series plot of temperature and dissolved oxygen for Hueco I Spring compared to precipitation data.

Hueco I has a greater temperature fluctuation with a C.V. of 2.9%. The mean of 21.5°C (70.7°F) and median of 21.3°C (70.34°F) are almost two degrees celsius lower than the temperatures at Comal and are much closer to the mean annual air temperature at New Braunfels. This is partially due to the shallower nature (as compared to Comal) of the ground-water system and the faster flow-through rate of the water.

The variations caused by rain are smoother at Comal than Hueco but the range in temperature variation due to rains was slightly greater at Comal. The analysis of variance test confirmed the significant difference in temperature between Hueco I and all the Comal Springs.

Specific conductance also remained relatively consistent for the sampling period at Comal Springs. Although there is some scatter in the plot for Comal 1 (Figure 16), a slight rising trend is observed for May and June. The conductivity meter had to be repaired in the middle of the sampling period, thus there is a break in the graphs of the data between late December, 1982 and early February, 1983. Hueco I has a very scattered plot of specific conductance (Figure 17), indicating the greater influence of precipitation and recharge on the spring waters. The C.V. at Hueco I was 8.1%, higher than the 7.0 for Comal I. Comal I showed a positive statistical correlation between conductivity and discharge while Hueco I demonstrated a negative correlation. Generally, there is a greater range and more fluctuation in specific conductance during storm events at Hueco than at Comal. This again depicts a shallower flow system at Hueco. The variations in conductance at Comal during rains are very abrupt, have less range, and are not as lasting as at Hueco. An in-depth discussion of the effects of storm events on the water chemistry of Comal and Hueco springs is presented in the following section.

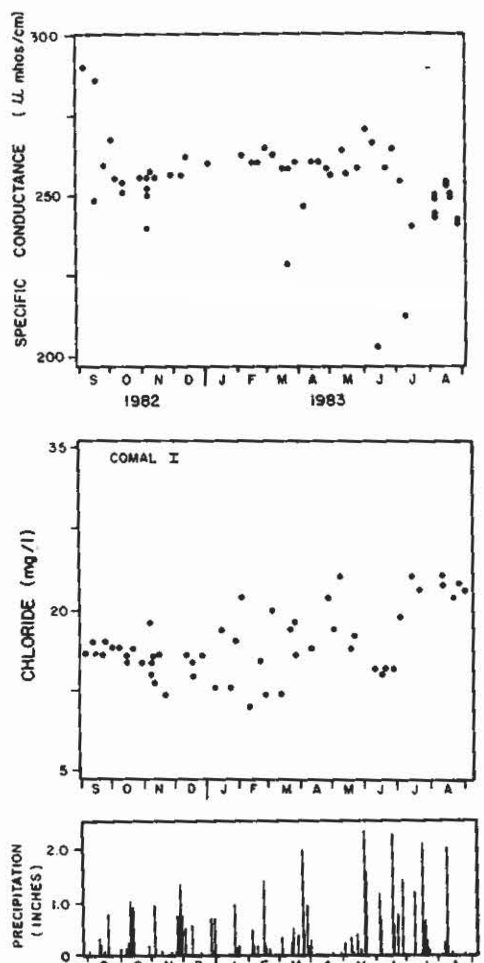

Figure 16. Time series plot of specific conductance and chloride concentrations for Comal 1 Spring compared to spring discharge data.

Dissolved oxygen was measured only during the last seven months of the investigation. These parameters, however, show some interesting and important results. On the plot of D.O. against time for Comal 1 (Figure 14), two peaks and one low are seen. The peaks occurred just between April and May, 1983, and from beginning to mid-August, 1983, where the D.O. appears to drop by the end of August. It is important to note that there was essentially no rain during April and early May, and that this corresponds dramatically with the decrease in D.O. for Comal 1. This demonstrates an impact from local precipitation events on water chemistry even when most recharge may be distant. A trough in the D.O. graph for Comal 1 also occurred from late June to mid-July, 1983. Even though there is a lack of data, the variations seem to be real. Comal 1 statistically has a higher range (4.41 - 5.80 mg/l), mean (5.77 mg/l), and median for dissolved oxygen compared to the other three orifices. This suggests for the first time that Comal I may have a shallow flow component or that some nearby recent, oxygen-rich meteoric waters are mixing with the spring water. It is also important to note that the maximum temperature of Comal 1 is about one degree celsius cooler than the other three Comal Springs. Hueco I has even higher D.O. values (4.58 mg/l to 6.38 mg/l) than Comal 1, with a mean of 5.77 mg/l and a median of 5.88 mg/l (Figure 15). It also has the highest C.V. of 9%. This is due to a much shallower and quicker flow-through system than Comal Springs.

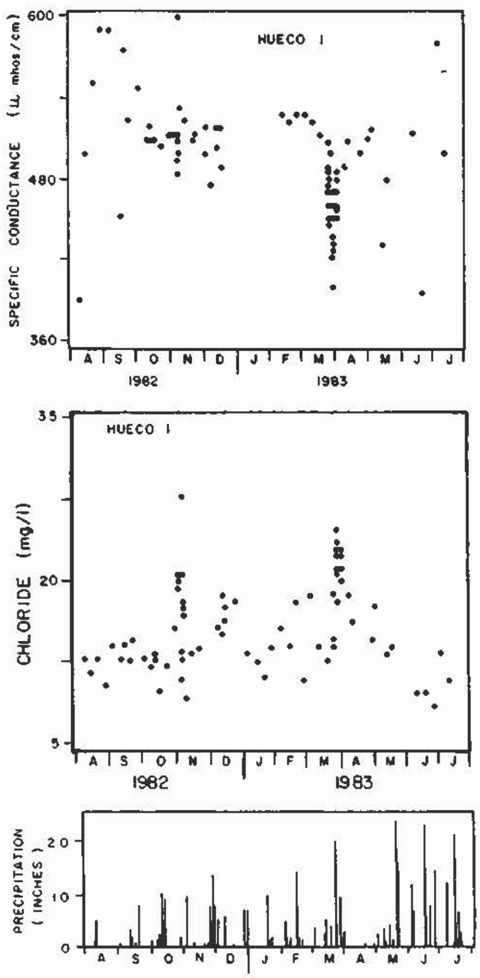

Figure 17. Time series plot of specific conductance and chloride concentrations for Hueco I Spring compared to annual precipitation data.

The analysis of variance tests confirm the dissolved oxygen differences between the spring groups.

Storm Responses

The effects of storm events on spring-water chemistry are demonstrated at Comal Springs by plots of selected chemical and physical parameters versus time for a few October rains (Figures 18 and 19). All spring orifices reacted similarly. Small rains occurring on October 6th and 8th, 1982 did not significantly change the spring-water chemistry, but an inch of rainfall on October 10th did. This larger rainfall increased the temperature and brought in soil nitrates. Fecal coliform bacteria and phosphate levels did not change. Calcium hardness increased but magnesium, sulfate, and chloride levels decreased. These data definitely demonstrate that some recent, local recharge waters are reaching the springs. This is contrary to prior thought, based on low tritium values (Pearson et al, 1975). A tritium value of 5.0 ± 0.5 T.U. was made for Comal 1 on a sample collected in October, 1984 during a severe drought. It is possible that during larger storms, a ground-water "wedge" of recent water may form near the Comal Springs orifices. There may be a few spots along the Comal Springs fault southwest of the springs where a limited amount of recent recharge can infiltrate and build up a wedge temporarily causing a steeper hydraulic gradient than other ground-water avenues providing spring flow. The amount and length of the effect of this ground-water wedge is related to the amount of precipitatioin and to the ground water stage. During low water-table conditions, the effects of large storm events will be greater. It is also possible that during very high water-table conditions, ground water may "spill over" the Comal Springs fault which usually acts as a ground-water barrier. This barrier usually prevents recharge waters west of the fault from reaching the springs. Monitoring of several storm events during the study year demonstrates that effects on spring-water chemistry remain three days to approximately three weeks, but in most cases, it is just a few days. A few future tritium measurements should be made at Comal Springs immediately after storm events to determine the validity of the ground-water wedge hypothesis.

The effects of a March, 1983 storm event on water chemistry at Hueco Springs was also monitored. For this study, an ISCO Model 2100 automatic sampler was utilized. The rains caused the water to become cloudy to muddy for up to several hours after a particular rain event. The discharge rose from 21.0 cfs (0.6 cms) before the first rain to a high of 53.0 cfs (1.5 cms) about 6.5 hours after the first rain (Figure 20). Generally, conductivity and calcium hardness decreased and magnesium hardness increased. Initially, a slug of calcium-rich water was pushed out of the spring system by the first rain. This could be due to the turbulent nature of the water causing increased dissolution, or it could be related to rapid dissolution of dried calcium minerals precipitated in the soil and along fractures. This hypothesis is possibly substantiated by the corresponding changes in pH (Figure 21).

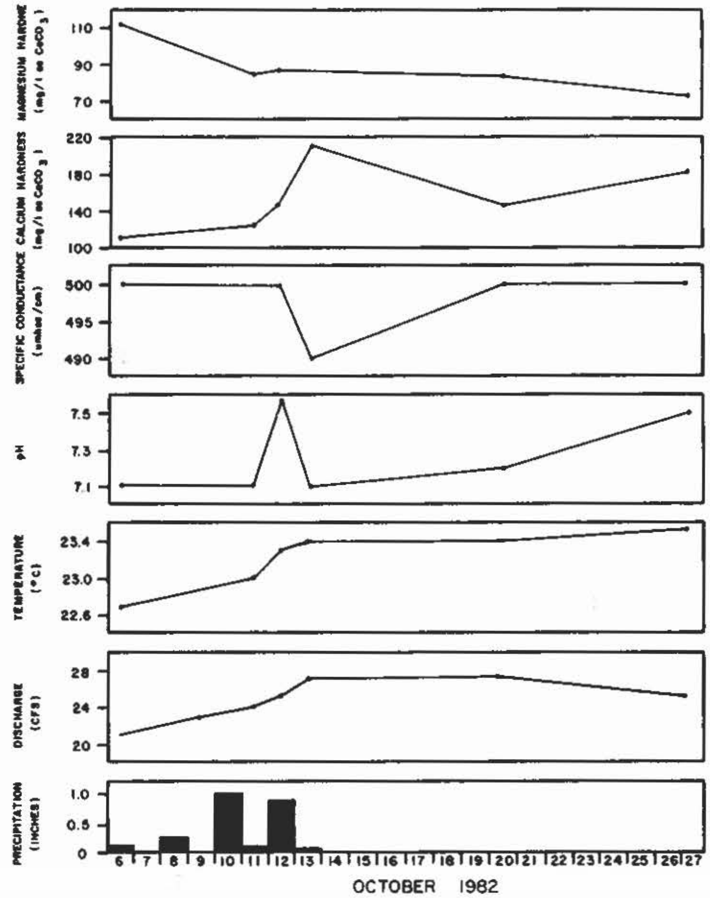

Figure 18. Plot of magnesium hardness, calcium hardness, specific conductance, pH, temperature, and discharge before, during, and after October, 1982 storms around Comal Springs.

Another explanation for fluctuations in calcium concentrations could be from water reaching the spring from different recharge areas along different flow paths. It is possible that harder water residing in one flow pathway being recharged near the spring was initially flushed out, causing a subsequent lowering of calcium concentration. Later, harder water in a second, more distantly recharged flow path, reached the spring outlet causing a second rise of the calcium concentration. Once the harder water was flushed out and dried calcium particles had been dissolved, the second storm had little affect on altering the amount of dissolved calcite.

Nitrate and chloride showed marked increases with discharge. As rain waters moved through the soil, sodium chloride was dissolved and soil nitrates added since it was March and just the beginning of the growing season. Also, the percolating waters may have carried surface contaminants to the spring from animal and human wastes. Although not plotted, fecal coliform counts increased as well. The analysis of these trends further supports the idea that rain waters rapidly move through the Hueco Springs system to emerge in a short period of time. The flow paths are shallow, and the water is therefore extremely susceptible to contamination.

IMPLICATIONS OF THE RESULTS AND RECOMMENDATIONS

The hydrochemistry data from the various orifices of the San Marcos Springs suggest that two nearly independent flow regimes contribute water to the springs. In addition, the ground-water tracer tests and the potentiometric surface map demonstrate that ground water from the San Antonio region moves northward confined within a narrow fault block and emerges primarily from just the southern orifices of the San Marcos Springs. This ground water appears to be separated from ground-water contributions from the Blanco River and Sink Creek areas by a fault-controlled, pressure boundary. The pressure boundary is believed to move slightly in response to changes in hydrostatic head between the two ground-water flow systems.

This new evidence now presents the possibility of preserving the springs and the endangered species by constructing a recharge/flood-control dam on the Blanco River. The proposed dam would have benefits whether placed on the Glen Rose Formation, or on the Edwards Limestone along a major losing stretch of the Blanco River. If an approximate 80 foot (24 m) dam is placed on outcrops of the Edwards Limestone, it could provide an effective means of raising the water table and likely would supply water to both the San Marcos and Kyle areas. Also, the ground-water divide between Barton Springs in Austin and the San Marcos

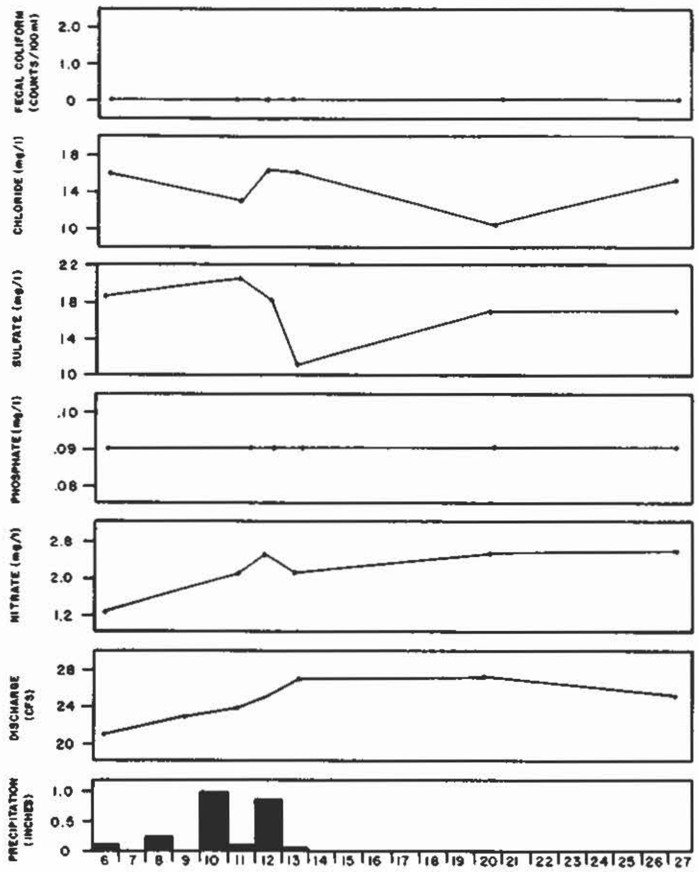

Figure 19. Plot of fecal coliform bacteria, chloride, sulfate, phosphate, nitrate, and discharge before, during, and after October, 1982 storms around Comal Spring.

Springs might change significantly due to the ground-water mound created by the dam. Therefore, both groups of springs may benefit. Siltation may prove to be a problem with time if the dam is built directly on the Edwards Aquifer. If the dam were to be built upstream on the Glen Rose Formation, the recharge rate could be controlled. A continued release of 120 cfs (3.4 cms) would provide the same maximum annual recharge rate of 85,900 acre-feet (1.06×10^8 m^3) which occurred in 1975. This method would also prevent excessive siltation of recharge points, but may not raise the water table as greatly. A good site for the proposed dam would be about two miles (3.2 km) upstream from the Halifax Ranch (Figure 13). In addition to recharge effects, the dam would significantly decrease downstream flooding and sustain flow longer into the summer when the Blanco River usually ceases to flow. The new lake created by the dam could have limited recreational use, but shoreline development would have to be controlled to preserve water quality. Due to monetary problems and legal battles, it would probably be 10 years before the dam could be completed. In the meantime, a diversion channel from the Blanco River to Tarbuttons Showerbath Cave should be constructed. Since the cave is within 20 feet of the river, cost would be minimal.

Faulting has hydrologically isolated Comal Springs from any large sources of local recharge. Therefore, a recharge dam cannot enhance the flow of the springs. Hueco Springs, on the other hand, receives significant amounts of local recharge, and its longevity could be ensured through building recharge structures at the headwaters of such creeks as Elm and Blieders. If the flow of Comal Springs is to be preserved, the amount of ground-water use by San Antonio must not increase significantly in the future. By converting, in part, to surface water supplies, reduction of ground-water pumpage would be possible. The building of major dams would be costly and unpopular in the San Antonio area. The present political atmosphere of federal budget cutting makes such a scheme appear even more unrealistic. A more logical and inexpensive method of preserving the Comal Springs flow would be to require mandatory water rationing in San Antonio sooner than presently dictated by the city reference well. Figure 22 shows the San Antonio reference well and the ground-water elevations used to determine which water conservation measures should take place. Since these elevations were somewhat randomly chosen based on the record low in 1956, it is recommended that the City Council raise the level at which voluntary and mandatory rationing begins to 640 feet and 625 feet, respectively. Since experts agree that the majority of summer water use in San Antonio is for watering lawns, such a regulation change would not pose a significant hardship to residents. The present monitoring system encourages ground-water waste at the expense of other aquifer users. San Antonio residents would still enjoy low water bills, and the springs would continue to flow.

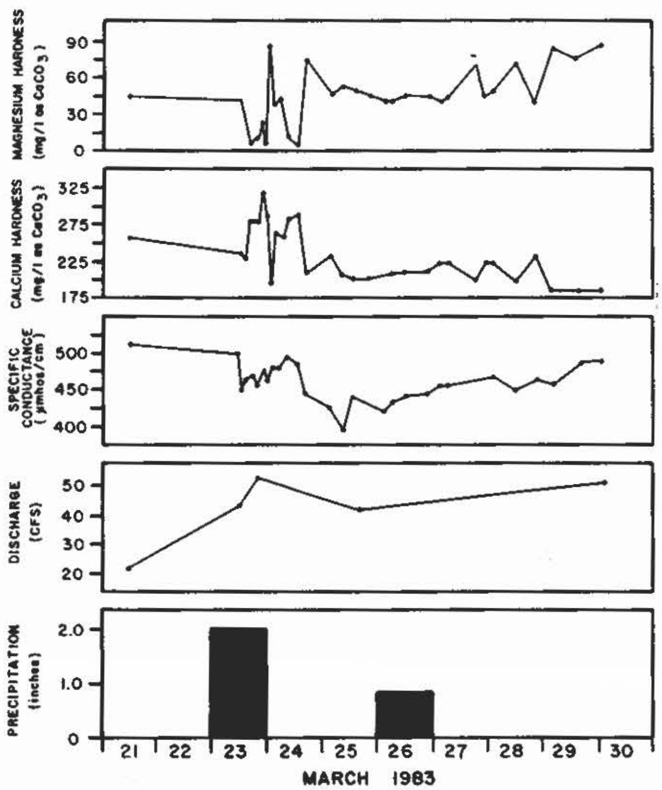

Figure 20. Plot of magnesium hardness, calcium hardness, specific conductance, and discharge before, during, and after March, 1983 storms around Hueco I Spring.

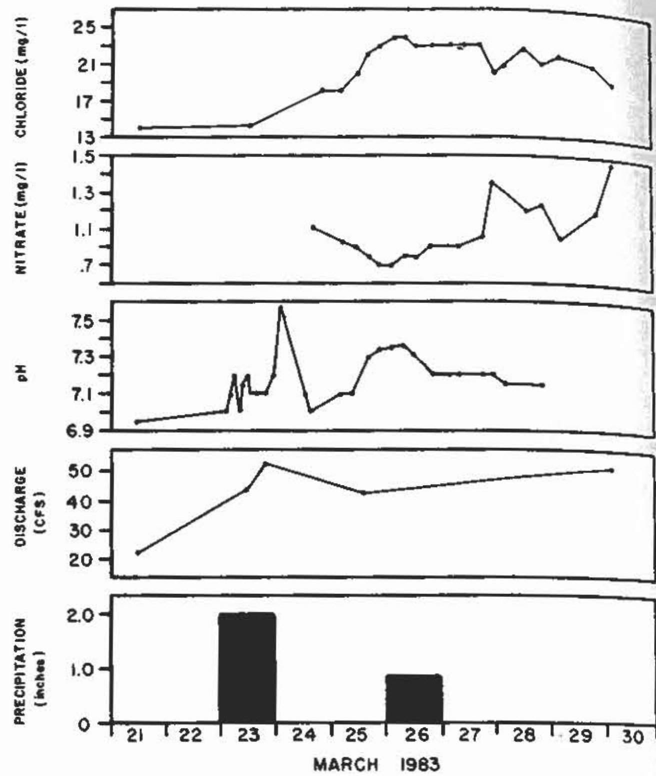

Figure 21. Plot of chloride, nitrate, pH, and discharge before, during, and after March, 1983 storms around Hueco I Spring.

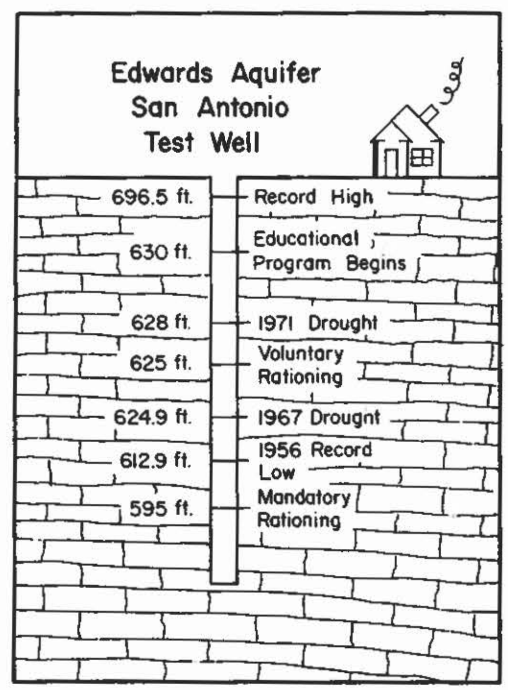

Figure 22. San Antonio reference well.

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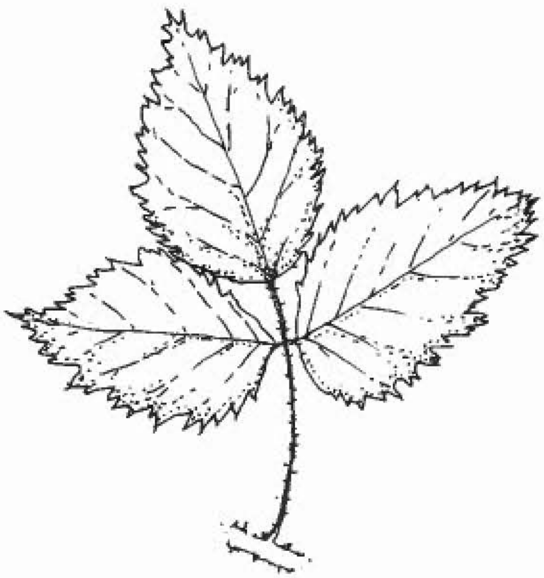
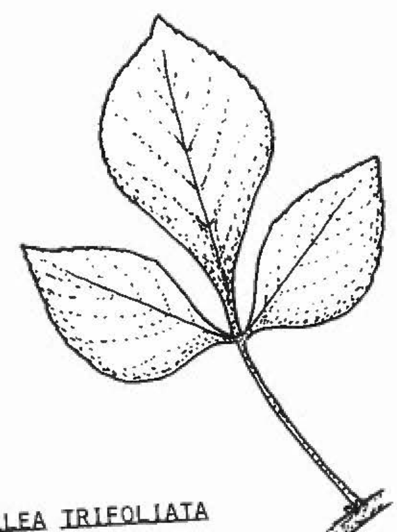


Rubus trivialis
Dewberry

Lindera benzoin
Spice wood



Ptelea trifoliata
Hop tree

RELATIONS BETWEEN AREAS OF HIGH TRANSMISSIVITY AND LINEAMENTS--THE EDWARDS AQUIFER, BARTON SPRINGS SEGMENT, TRAVIS AND HAYS COUNTIES

Laura De La Garza
City of Austin
Office of Environmental
Resource Management
Austin, TX 78767

Raymond M. Slade, Jr.
U.S. Geological Survey
Federal Building, 6th Floor
Austin, TX 78701

ABSTRACT

The relationship between the productivity of wells with respect to the location of lineaments has been investigated for 47 wells in that part of the Edwards aquifer which discharges to Barton Springs. Controlled aerial mosaics were used to map two sets of lineaments (short and long) by the use of different techniques. Transmissivities were then estimated for all wells with specific capacity data. The distance from each of the wells to the nearest short and long lineament was then determined. Wells located greater than 300 feet from short-lineaments had transmissivities which ranged from less than 25 to 2,800 gal/day/ft and averaged 434 gal/day/ft. Transmissivities for wells within 300 feet of short lineaments averaged 56,300 gal/day/ft and ranged from 200 to 350,000 gal/day/ft.

There is a strong correlation between increased water well productivity and decreased distances to short lineaments. However, no correlation is evident between well productivity and distances to long lineaments. Locations of short lineaments can therefore be used to increase the probability of locating high yield wells in the Edwards aquifer associated with Barton Springs.

INTRODUCTION

Linear features on the surface of the earth have attracted the attention of geologists for over one hundred years. This interest has grown most rapidly since the introduction of aerial photographs into geological studies. Geologists have recently proven that lineaments perceived in remotely sensed images are reliable indicators of geologic structure (Caran and others, 1982). Lineaments have been used in many applications: petroleum and mineral exploration (Blanchet, 1957); nuclear energy facility siting (Seay, 1979); geothermal assessments (Woodruff and others, 1982); and water resource investigations (Lattman and Parizek, 1964). Lattman and Parizek (1964) established a relationship between the occurrence of groundwater and fracture traces for carbonate aquifers, and in particular that lineaments are underlain by zones of localized weathering and increased permeability and porosity. LaRiccia and Rauch (1977) tested this theory on a limestone aquifer in Frederick Valley, Maryland. They reported that short lineaments are usually associated with higher transmissivities, thus greater water well productivities.

Lineaments have been called lineations, linears, fracture traces, and many other names. Woodruff and others (1982) did a thorough review of published works on lineaments and have proposed a concise terminology, and a systematic method of perceiving and interpreting lineaments that improves data reproducibility. Their terminology and methodology have been used within this report.

The purpose of this report is to determine and present the relation between productivity of water wells and proximity to lineaments in that part of the Edwards aquifer that discharges to Barton Springs. If wells with high yields can be related to the location of lineaments, then the locations of lineaments could be useful in locating zones of high productivity in the aquifer, and areas of high recharge potential in the unsaturated zone of the aquifer. Furthermore, flow in the Edwards aquifer is primarily through the cavities and caves associated with faults, fractures, and joints. (Slade, 1984). The intent of this report therefore is to test the hypothesis that lineaments relate to fracture zones--areas of greater hydraulic conductivity.

DESCRIPTION OF STUDY AREA AND HYDROGEOLOGIC SETTING

The study area for this report is that part of the Edwards aquifer that discharges to Barton Springs. It extends from a discharge boundary formed at the Colorado River in the north, to a southern boundary about 25 miles south of the river--a surface water divide which separates the Blanco River Basin from that of Onion Creek. The western boundary of the aquifer is the western extent of the Edwards Limestone (mainly controlled by the Mt. Bonnell Fault), and the eastern boundary, known as the "bad-water" line, is the eastern limit of water within the aquifer which contains less than 1,000 mg/l dissolved solids (figure 1). These boundaries form a hydrologically independent segment of the Edwards aquifer which covers about 155 square miles. The westernmost 90 square miles of the aquifer area is within the recharge zone--that area which covers the outcrop of the Edwards and Georgetown Limestones. About 85 percent of the recharge occurs in the main channels of six major streams that cross the recharge zone. These creeks have a total combined drainage of 264 square miles upstream from the recharge zone,--an area called the contributing zone. The main discharge point of this segment of the Edwards aquifer is Barton Springs.

The aquifer is composed of the Edwards and Georgetown Limestones, a series of limestones and dolomites which range from 400 to 460 ft thick where not outcropped. Where exposed at the surface in the recharge zone, the aquifer varies from about 100 to 460 feet thick. The upper confining layer is the Del Rio Clay which ranges from 60 to 75 ft thick, and the lower confining unit is the Walnut Formation

in Abbott, Patrick L. and Woodruff, C.M., Jr., eds., 1986, **The Balcones Escarpment, Central Texas:** Geological Society of America, p. 131-144

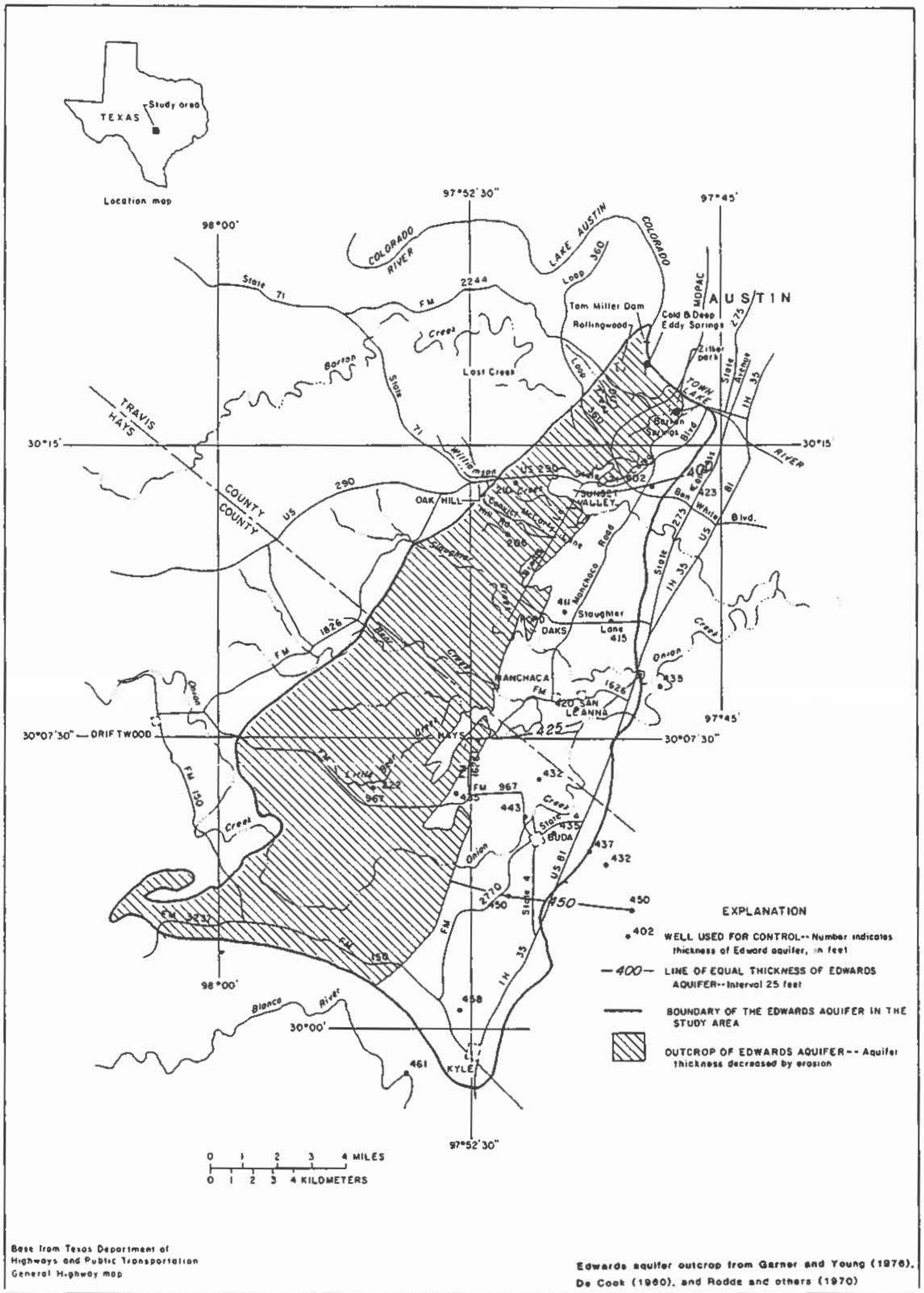


Figure 1. Boundary of the Edwards aquifer--Barton Springs Segment (Slade and Others, 1985).

which ranges from 15 to 60 ft thick. The Balcones Fault Zone extends over much of the aquifer creating numerous fault blocks "stair stepping" downward to the east, with vertical displacements of as much as 200 ft. However, no evidence has been presented to indicate that the aquifer is discontinuous, thus groundwater flow probably is not greatly impeded by faults (Slade, and others, 1985).

DEVELOPMENT OF POROSITY AND PERMEABILITY

Significant porosity in the Edwards aquifer was created along particular bedding planes through dissolution by meteoric water during an interval of subaerial exposure at the close of the Edwards Limestone period of deposition (Abbott, 1976). Enhanced porosity also occurs laterally and vertically along faults and fractures as a result of enlargement by dissolution. Laterally continuous cavities are thought to be caused by dissolution of the limestone along faults. Wermund and others (1978) compared the incidence of caves with the incidence of short fractures (lineaments) on the Southern Edwards Plateau and reported that cave frequency increases as fracture incidence increases. Parizek (1975) shows how various factors influence cavity distribution in carbonate rocks (figure 2). Furthermore, interpretation of geophysical and drillers' logs for many wells in the study area indicates that most wells that penetrated cavities within the aquifer are near faults (Slade and others, 1985). Wells that have penetrated cavities commonly have high yields.

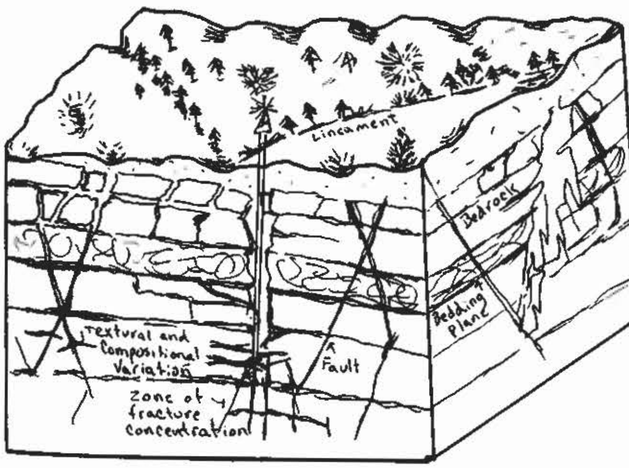


Figure 2. Block diagram showing various structural and stratigraphic influences on porosity development (modified from Parizek, 1975).

DEFINITION OF LINEAMENTS AND METHOD OF INVESTIGATION

Woodruff and others (1982) define lineaments as a figure (either simple or composite) that 1) is perceived in an image of a solid planetary body; 2) is linear and continuous; 3) has definable end points and lateral boundaries; 4) has a relatively high length to width ratio and hence a discernible azimuth; and 5) is shown or presumed to be correlative related to stratigraphy or geologic structure.

A "false lineament" is defined as a percieved lineament which meets all but criteria number 5 as described above. "False lineaments" could be: 1) cultural manifestations that do not coincide with linear topography such as fencelines, roads, pipelines, railroads and animal trails; 2) artifacts of imaging process or perceptual aberrations (illusions); or 3) geomorphic features that are not controlled by stratigraphy or geologic structure. "False lineaments" are sometimes mapped as true lineaments. However in the process of transferring the lineaments marked on aerial photographs, most if not all false lineaments are thought to be eliminated from the study.

Lineaments are polygenetic and inherently ambiguous features. They are ambiguous because they cannot always be field verified, nor are they precisely reproducible. Lineaments are polygenetic in that they owe their expression to a number of different causes. Lineaments could be 1) straight stream and valley segments, 2) aligned surface sags and depressions, 3) soil tonal changes revealing variations in soil moisture, 4) alignments in vegetation, 5) vegetation type and height changes, and 6) abrupt topographic changes. All of these phenomena might be a result of structural phenomena such as fault, joint sets, or folds.

The method employed for this study began by obtaining controlled mosaics of 1:20,000 black-and-white aerial photographs flown in 1937 by Tobin Research, Inc. Six mosaics were needed to cover the study area which corresponds to the Austin West, Buda, Driftwood, Mountain City, Oak Hill, and Signal Hill, 7.5 minute quadrangle maps of the U.S. Geological Survey.

Two sets of lineaments were identified--short and long sets. Both sets were viewed by three interpreters; however the mapping and viewing methods were different. For short lineaments, the six mosaics were viewed individually for two 20 minute sessions by each interpreter, thus a total of 120 minutes of viewing time for each 7.5 minute map. In order for a linear feature to be mapped as a lineament, a minimum length of 1/2 inch on image (about 1000 feet on the ground) was established. No maximum length was set, therefore the maximum length could be the length of a diagonal line across the 7.5 minute map. The end points of each lineament were identified with arrows then transferred to a set of maps (figures 3-8).

For the long lineaments the same set of mosaics were used, but the six photo mosaics were taped together on the floor of a large room and viewed concurrently by all three investigators. In viewing long lineaments, minimum lengths of one foot on the image (about 4.5 miles on the ground) were identified only when all three interpreters agreed on their presence. The lineament was then marked by tape and later transferred to the same set of maps. Again, the main difference in short and long lineaments lies in the method that they were percieved.

METHOD OF ESTIMATING WELL YIELDS FROM PUMP DATA

Well data were obtained from the U.S. Geological Survey (USGS). Information for all wells with recorded pump tests was gathered by the USGS from the Texas Water Development Board for a study which simulated the flow of Barton Springs and associated Edwards aquifer (Slade and others, 1985).

58-42

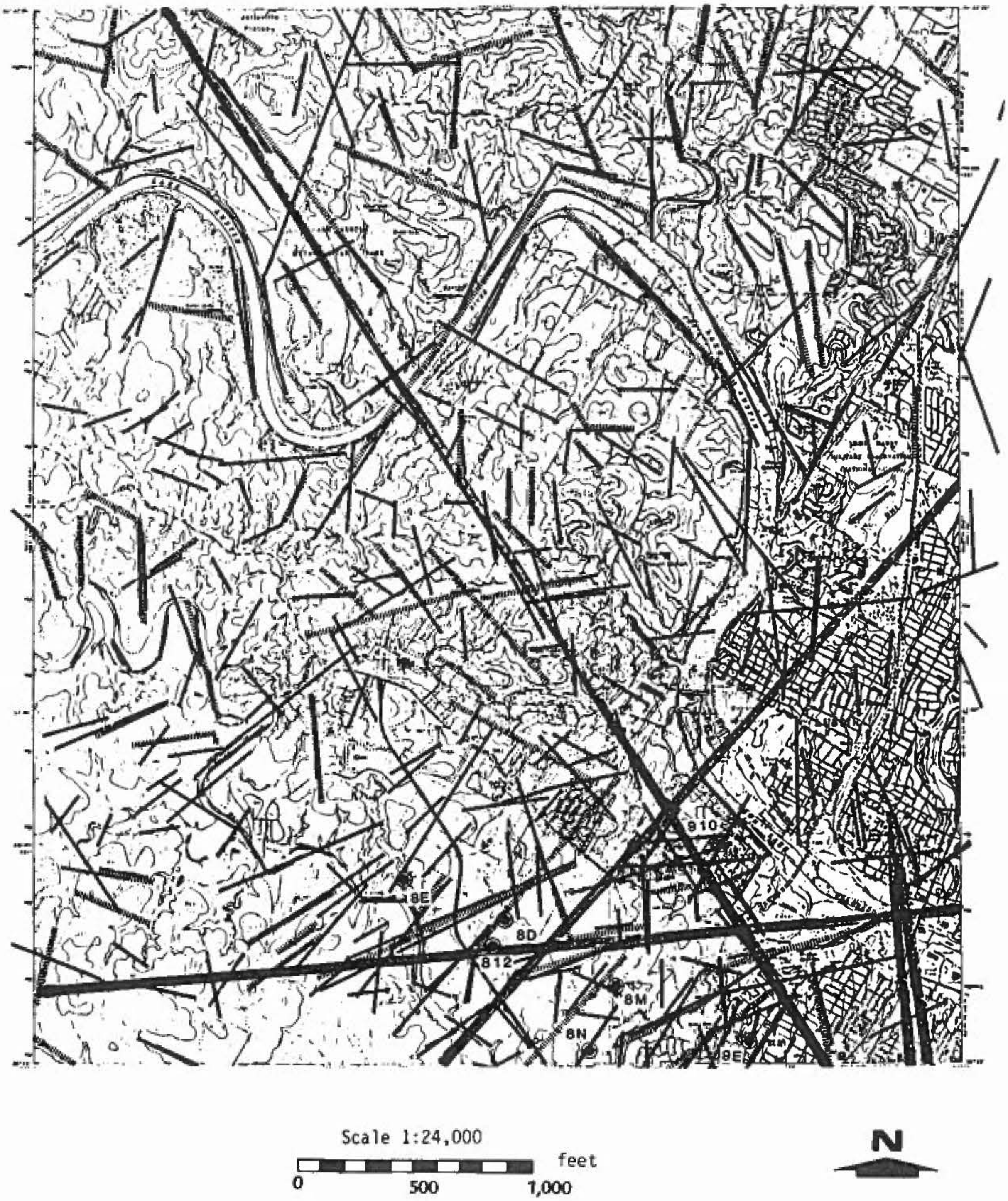


Figure 3. Locations of the wells used in the study and short and long lineaments mapped on the Austin West, Texas 7.5" U.S.G.S. quadrangle map.

Figure 4. Locations of the wells used in the study and short and long lineaments mapped on the Oak Hill, Texas 7.5" U.S.G.S. quadrangle map.

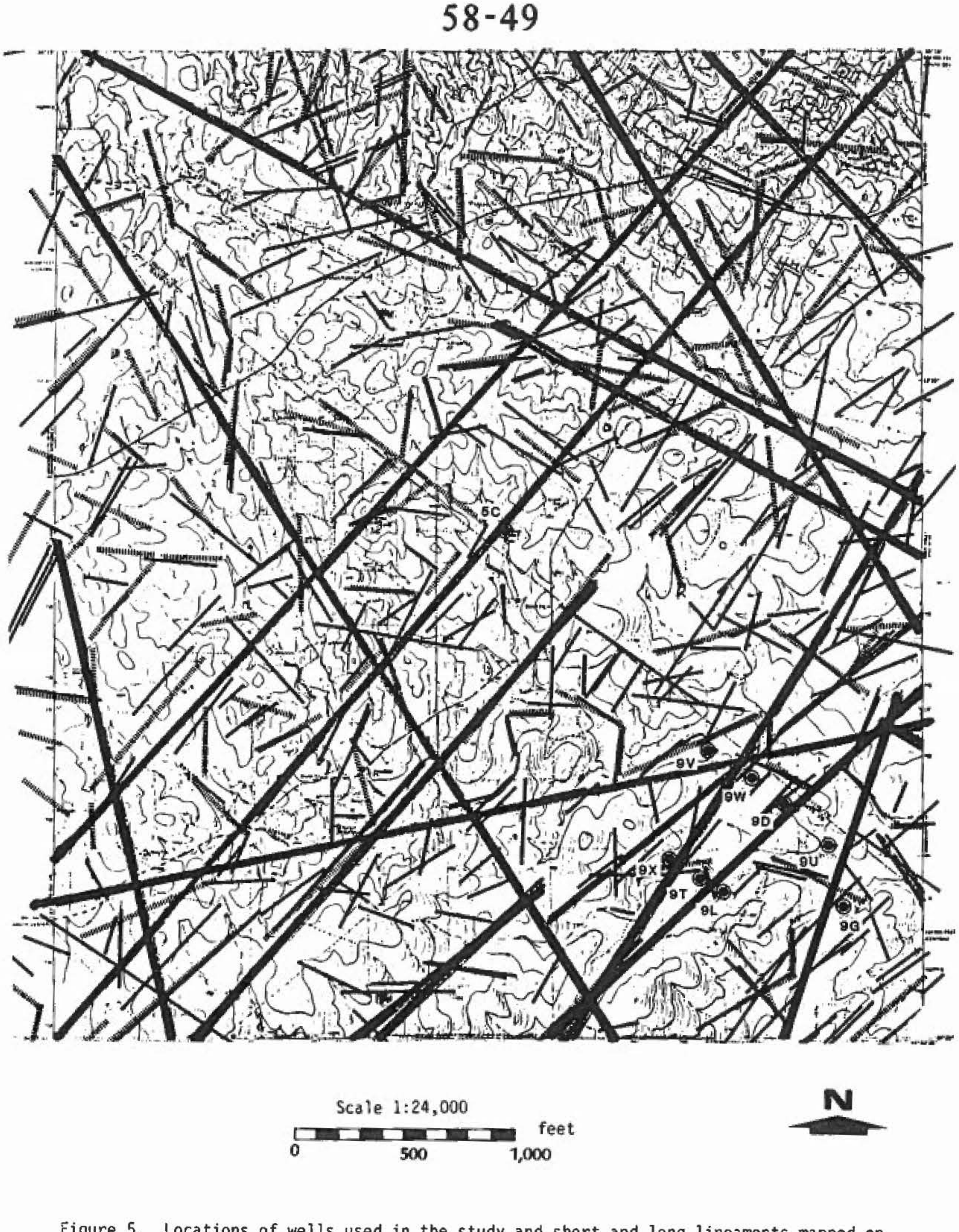


Figure 5. Locations of wells used in the study and short and long lineaments mapped on Signal Hill, Texas 7.5" U.S.G.S. quadrangle map.

58-58

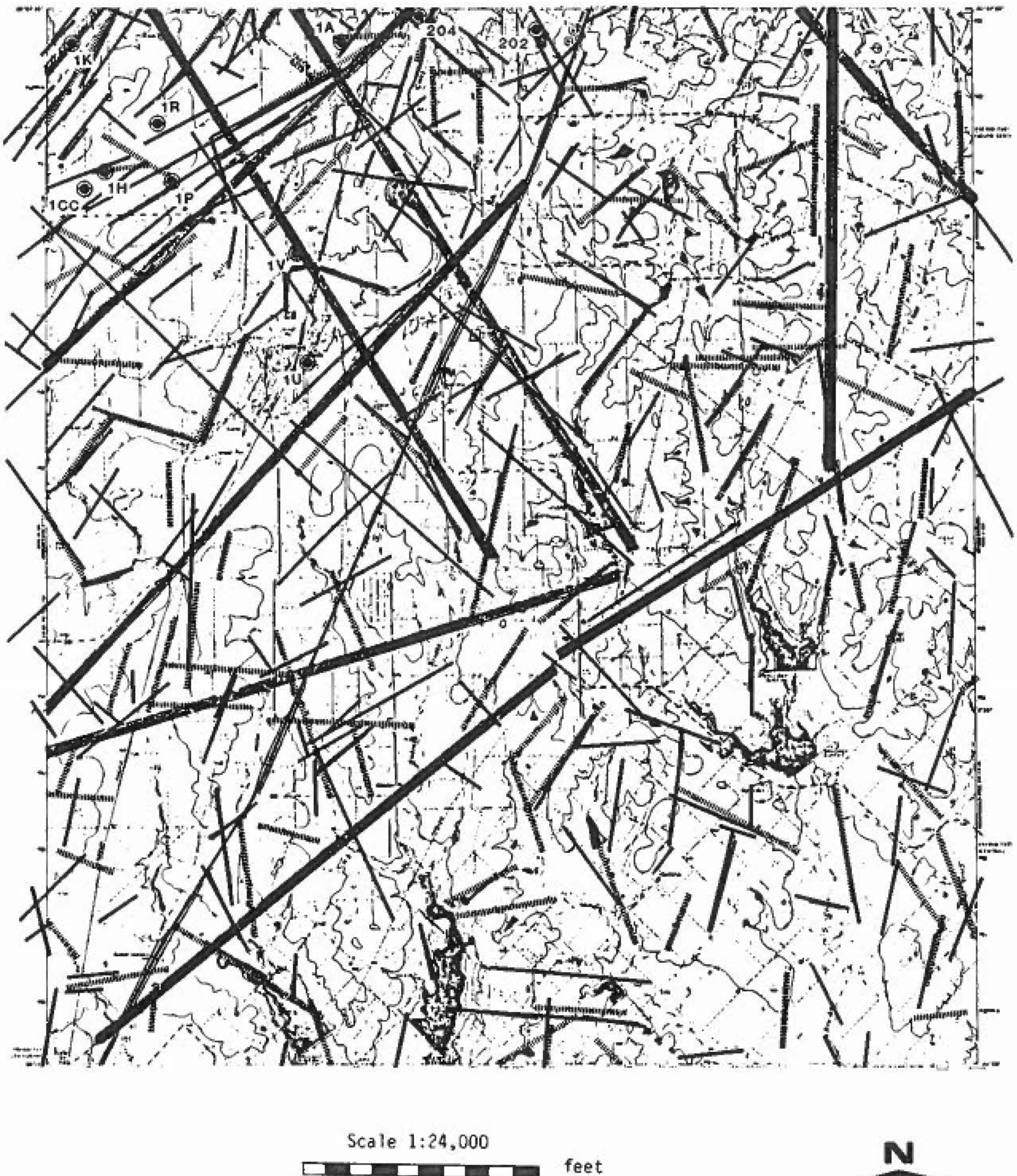


Figure 6. Locations of the wells used in the study and short and long lineaments mapped on the Buda, Texas 7.5" U.S.G.S. quadrangle map.

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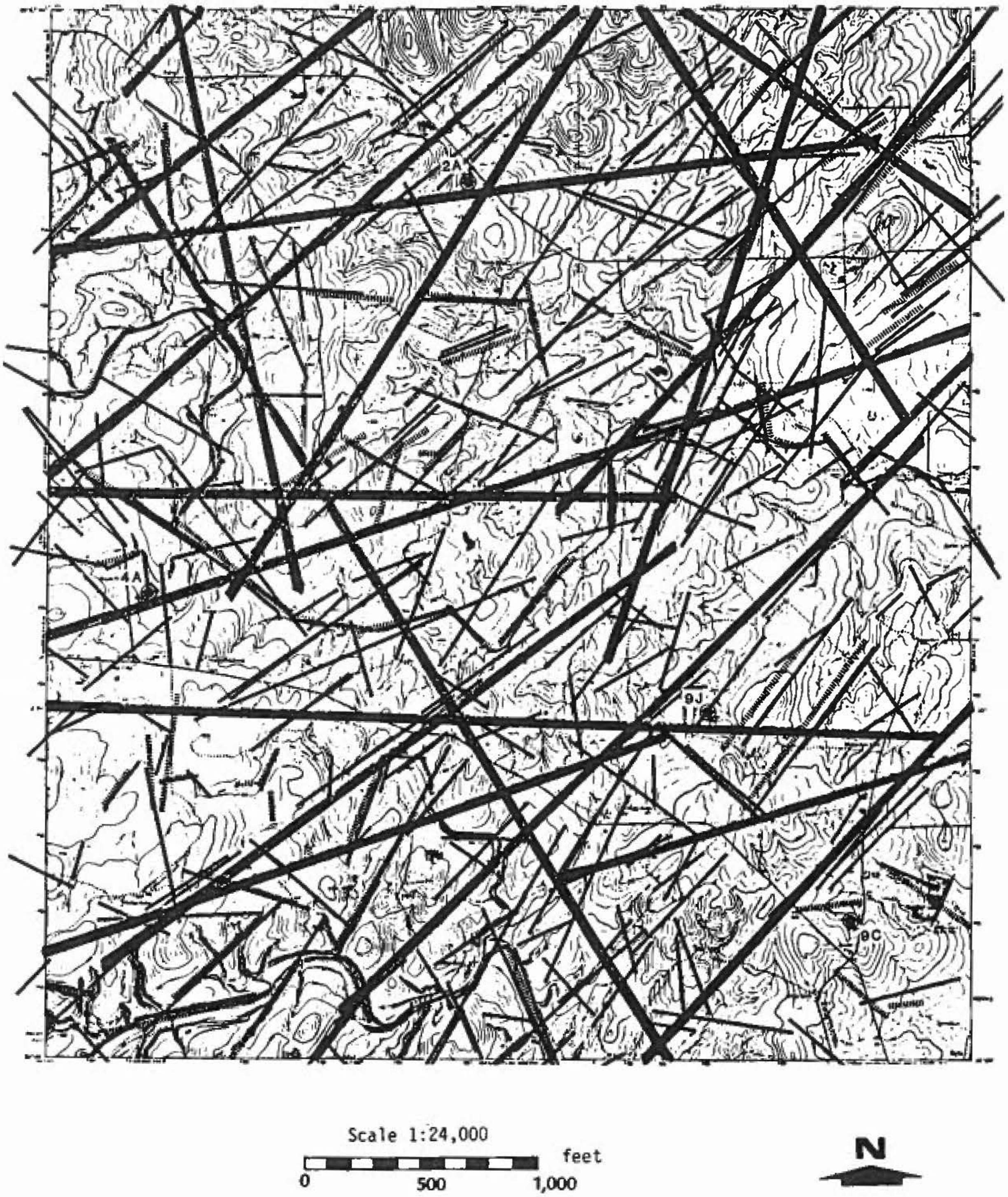

Figure 7. Locations of the wells used in the study and long and short lineaments mapped the Mountain City, Texas 7.5" U.S.G.S. quadrangle map.

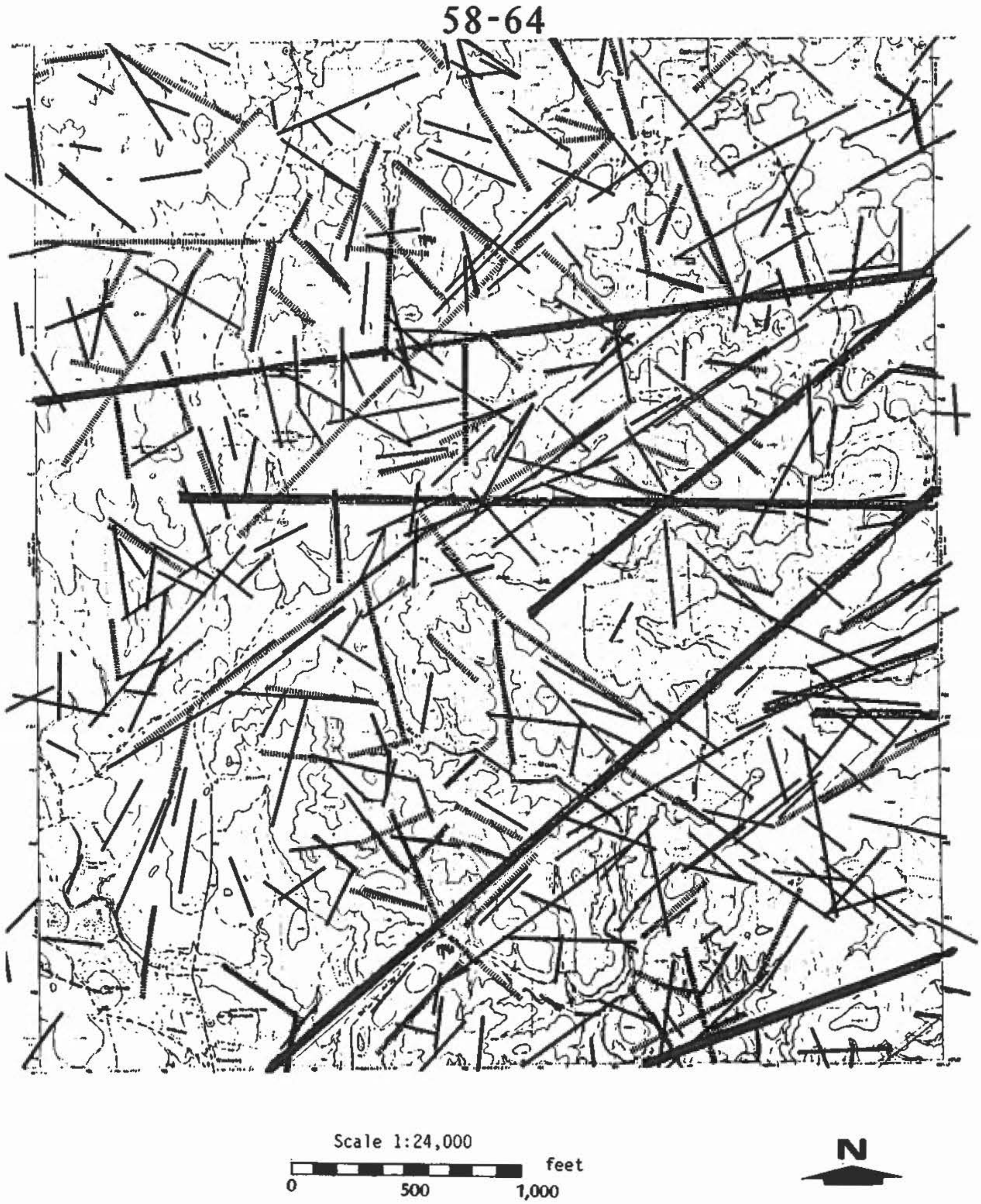

Figure 8. Locations of the wells used in the study and short and long lineaments mapped on the Driftwood, Texas 7.5" U.S.G.S. quadrangle map.

No known aquifer-test data exist for the study area (Slade and others, 1985). Therefore, transmissivities were estimated from specific capacities. For this study, water well yields were represented by transmissivities of the aquifer at the well location. Transmissivities were used rather than specific capacities because transmissivities represent the hydraulic characteristic of the aquifer, whereas specific capacities can be a function of how efficient wells are completed and developed.

Pumpage and drawdown data were used to compute specific capacities of the wells. Transmissivities were estimated from specific capacities by a method derived by Rex R. Meyer (Bentall, 1963). Meyer created a graph that relates well diameter, specific capacity (SC), transmissivity (T), and storage (S). The graph was prepared by 1) computing, for various values of T and S, the theoretical drawdown in wells having different diameters, 2) computing the specific capacity of those wells (on the assumption that they were 100% efficient), and 3) plotting the specific capacity against S to form a family of curves which represent the different values of T.

Meyer explains that the graph has certain limitations--however these limitations do not apply to the Edwards aquifer. A principal factor affecting the transmissivity at a well is the entrance loss of water to the bore. The graph is based on the assumption that the wells are 100 percent efficient or, in other words, the water level is the same inside and immediately outside the casing or screen when the wells are pumped. This assumption that wells are 100 percent efficient applies to wells within the Edwards aquifer, most of which are uncased within the aquifer. Thus good communication between the bore and aquifer should exist (Slade, personnal comm., 1986).

Another factor affecting the transmissivity at a well is the diameter of the well. The well diameters of 6, 12, and 24 inches are shown on the graph and are considered to be the effective diameters of the well. Meyer explains the actual and effective diameter may be different for wells in unconsolidated aquifers. However, if an aquifer is composed of consolidated rocks, as is the Edwards aquifer, the effective diameter should not appreciably vary from the actual diameter of the well. It is also evident from the graph that differences in diameters do not greatly affect the transmissivities.

A time interval of one day was used for computing the specific capacities on the graph. It was noted that an error will be introduced if the specific capacity determined in the field is based on shorter or longer periods of pumping. Meyer (Bentall, 1963) notes that the amount of this error is small for high values of T and low values of S but increases substantially for low values of T and high values of S. This error will be small for wells in the Edwards, where small values of S and large values of T normally occur.

The graph shows that large changes in storage correspond to relatively small changes in T and SC; therefore, any errors in S would not significantly affect the values of T. Reasonable values for S can be estimated based on previous studies done on the Barton Springs segment of the Edwards aquifer. Slade and others (1985) estimated storage coefficients using a two-dimensional, finite-difference ground-water model of the study area; specific yield was calibrated for a transient-state simulation using time-dependent gauged or measured data for recharge, discharge, and water levels. The mean specific yield for the unconfined part of the aquifer was determined to be 0.014, and the coefficient of storage of the confined portion was calculated to be .00005. Specific yield is defined as the volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in the water table. Specific yield increases with porosity, and because of the karstic nature of the aquifer, specific yield also increases with hydraulic conductivity (Slade and others, 1985). Slade reported that hydraulic conductivities generally increased with proximity to Barton Springs, and thus a similar pattern for distribution of specific yield probably exists.

INTERPRETATION AND CONCLUSIONS

Locations of the wells with specific capacities were plotted on the composite set of lineament maps, figures 3-8. A total of forty-seven wells were available for this analysis. The specific capacities, and distance from each well to the nearest lineament is summarized in Table 1. Distances were recorded to the nearest 50 feet. The transmissivities for the 47 wells range from less than 25 to 350,000 gal/day/ft. The distances from these wells to short lineaments vary from 0 to more than 1000 feet. However, all 12 wells which had T's greater than 10,000 gal/day/ft were within 300 feet of a short lineament. Also 17 of 20 wells with T's greater than 1,000 gal/day/ft were within 300 feet from a short lineament. Of the 27 wells with T's less than 1,000 gal/day/ft, 21 were greater than 300 feet of a short lineament. The 20 wells with T's greater than 1,000 gal/day/ft were located an average of 190 feet from short lineaments, whereas the 27 wells with T's less than 1,000 gal/day/ft were located at an average distance of 520 feet from short lineaments. A correlation therefore exists between higher transmissivities and decreased distances to short lineaments.

Figures 9 and 10 show the distance from each well to the nearest lineament plotted against the estimated T for each well. A correlation can be made from the short lineament set; however there does not appear to be any type of correlation between well transmissivities and proximity to longer lineaments.

A correlation between areas of increased aquifer productivity and decreased distances to short lineaments can be made. Some lineaments can therefore be used to increase the probability of locating high yield zones of the Edwards aquifer. This association probably indicates that lineaments are associated with fracture zones and areas of solution porosity and high permeability.

There are four limitations to conclusions from this report. First of all, most of the well locations have not been field verified. Therefore the distances from the wells to the nearest lineaments are subject to error. Also, the locations of lineaments marked on the mosaics are subject to error in the transferring process, which could affect the distances between lineaments and wells. Next, the specific capacities were obtained form drillers logs. It is not known whether or not

Table 1. Summary of wells with specific capacities, estimated transmissivities and relative distance to nearest lineament.

OBS	WELL NO.	DISCHARGE (gal/min)	DRAWDOWN (feet)	SC (gal/min/ft)	T (gal/ft/day)	ZONE	1) (feet)	2) (feet)
1	58-42-812	20.0	1.5	13.300	26,000	WT	300	150
2	58-42-910	500.0	2.5	200.000	300,000	WT	0	1,250
3	58-42-08M	100.0	60.0	1.700	2,800	WT	200	2,000
4	58-42-08N	100.0	5.2	20.000	35,000	WT	0	4,250
5	58-42-09E	30.0	0.2	150.000	350,000	WT	200	650
6	58-42-08E	20.0	0.0	20.000	38,000	WT	200	3,300
7	58-42-08D	30.0	0.0	30.000	55,000	WT	100	1,250
8	58-49-05C	8.0	60.0	0.130	250	WT	1,000	12,500
9	58-49-09X	6.0	235.0	0.026	25	WT	400	250
10	58-49-09W	5.2	189.0	0.028	25	WT	650	700
11	58-49-09V	15.0	345.0	0.043	40	WT	550	700
12	58-49-09U	6.0	120.0	0.050	50	WT	650	650
13	58-49-09T	10.0	50.0	0.200	300	WT	400	500
14	58-49-09L	10.0	70.0	0.143	225	WT	300	600
15	58-49-09G	10.0	270.0	0.037	35	WT	400	550
16	58-49-09D	20.0	0.0	20.000	38,000	WT	200	300
17	58-50-402	45.0	60.0	0.750	1,100	WT	0	2,800
18	58-50-505	8.0	50.0	0.160	300	ART	250	550
19	58-50-506	25.0	20.0	1.250	2,800	ART	800	1,200
20	58-50-704	942.0	12.0	78.500	170,000	WT	0	0
21	58-50-717	25.0	40.0	0.625	900	WT	300	2,800
22	58-50-822	40.0	70.0	0.570	1,200	ART	700	4,600
23	58-50-810	20.0	130.0	0.150	350	ART	650	1,000
24	58-50-830	45.0	160.0	0.280	550	ART	500	600
25	58-50-835	270.0	12.0	22.500	58,000	ART	0	3,500
26	58-50-04C	15.0	30.0	0.500	750	WT	350	1,200
27	58-50-04D	8.0	20.0	0.400	500	WT	550	2,300
28	58-50-04G	10.0	70.0	0.140	200	WT	750	550
29	58-50-831	12.0	0.0	12.000	79,000	ART	300	400
30	58-50-7CC	85.0	25.0	3.400	5,800	WT	0	250
31	58-50-06B	15.0	60.0	0.250	495	ART	200	6,500
32	58-50-05D	20.0	30.0	0.660	675	WT	950	150
33	58-50-04A	7.0	15.0	0.466	600	WT	350	0
34	58-57-09J	25.0	150.0	0.167	290	WT	0	450
35	58-57-09C	5.0	100.0	0.050	50	WT	800	2,200
36	58-57-04A	13.0	95.0	0.137	200	WT	600	200
37	58-57-02A	5.0	205.0	0.024	25	WT	700	200
38	58-58-01A	20.0	20.0	1.000	1,500	WT	250	800
39	58-58-01V	20.0	218.0	0.090	150	WT	900	50
40	58-58-01U	15.0	30.0	0.050	700	WT	450	1,500
41	58-58-01P	40.0	0.0	40.000	80,000	WT	100	1,550
42	58-58-01K	660.0	12.0	55.000	12,000	WT	200	0
43	58-58-01H	20.0	0.0	20.000	38,000	WT	0	2,750
44	58-58-1CC	20.0	265.0	0.075	100	WT	600	1,600
45	58-58-202	42.0	185.0	0.230	475	ART	350	1,200
46	58-58-204	24.0	18.0	1.300	3,000	ART	250	50
47	58-58-01R	25.0	100.0	0.250	375	WT	450	2,100

1) distance from well to nearest short lineament
2) distance from well to nearest long lineament

steady state conditions were reached before water level declines were measured, or if constant discharges were maintained throughout the tests. Finally, conclusions are based on only 47 wells. It is not known if this is a representative sample of wells with varying specific capacities and locations with respect to lineaments.

ACKNOWLEDGEMENTS

The lineaments were derived by the mapping work done by Fred Snyder, Albert E. Ogden and C. M. Woodruff. The lineament maps used in the study are available from the City of Austin's Department of Environmental Protection. Special thanks to Fred Snyder for the time and effort that went into the compilation of the lineaments and also for the idea and encouragement to do this study.

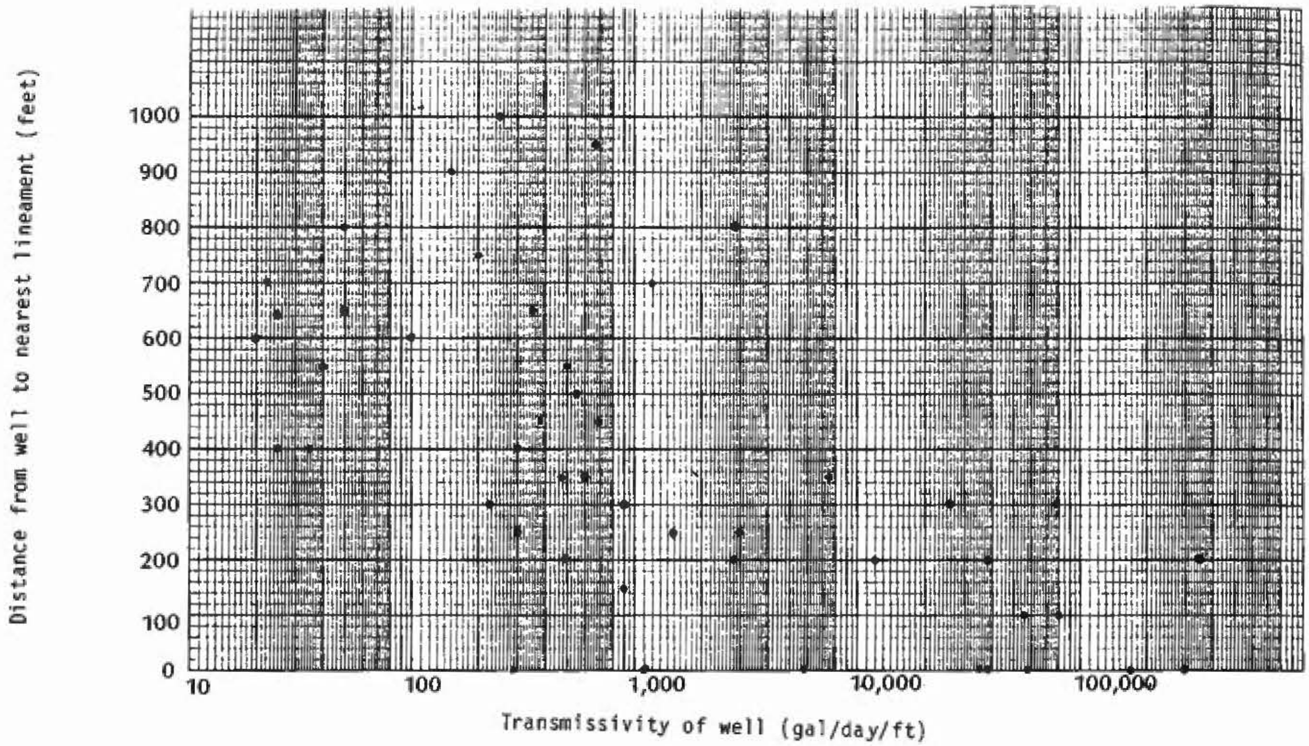

Figure 9. Relation between distance of wells to short lineaments and transmissivities.

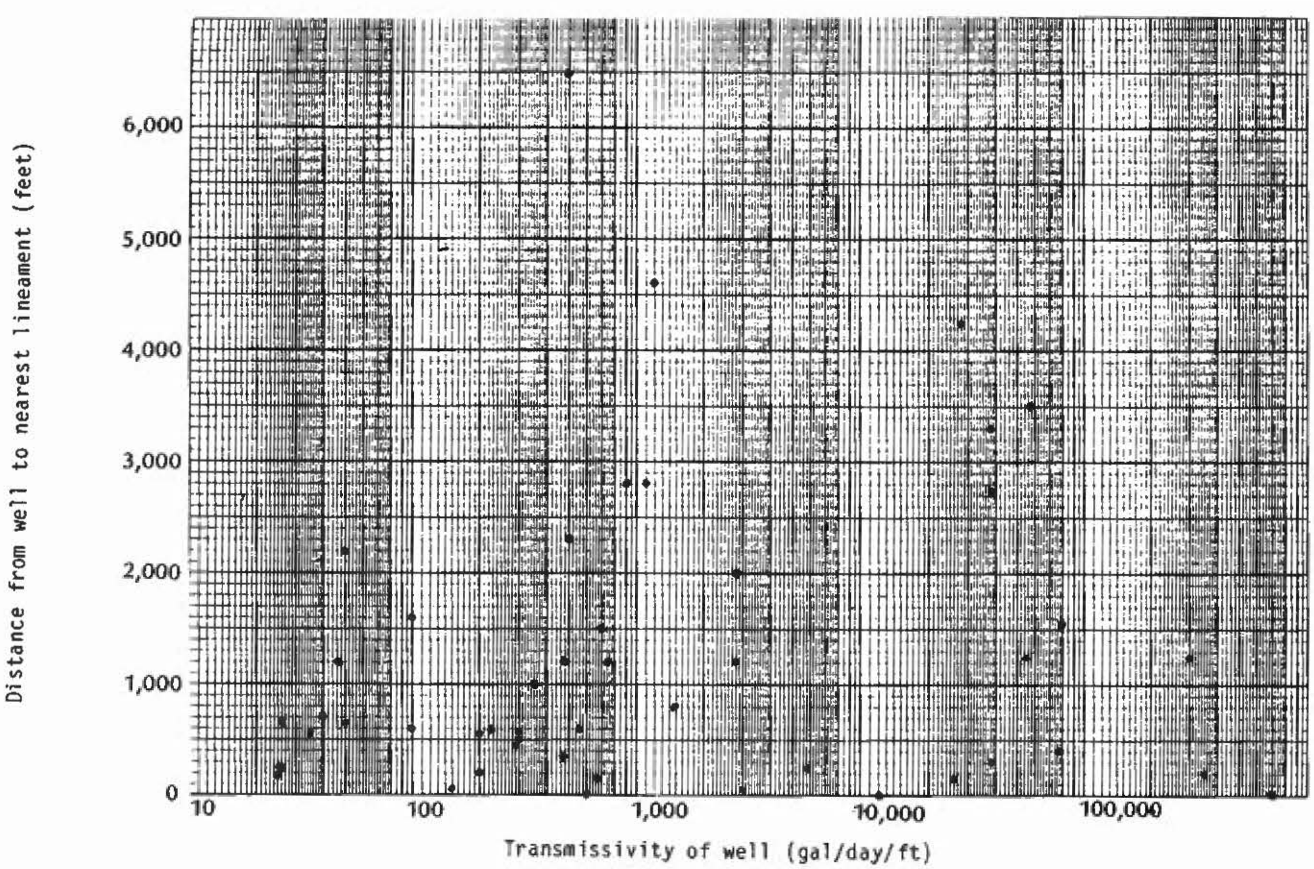

Figure 10. Relation between distance of wells to long lineaments and transmissivities.

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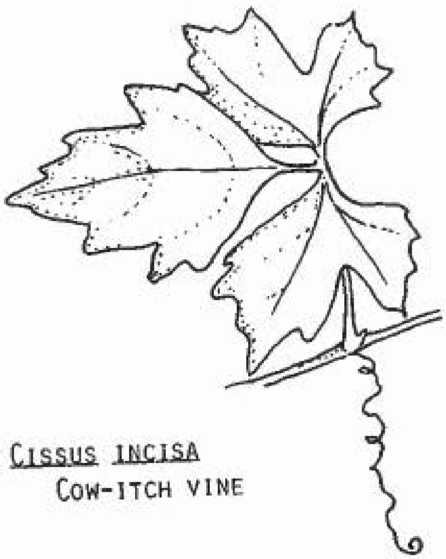
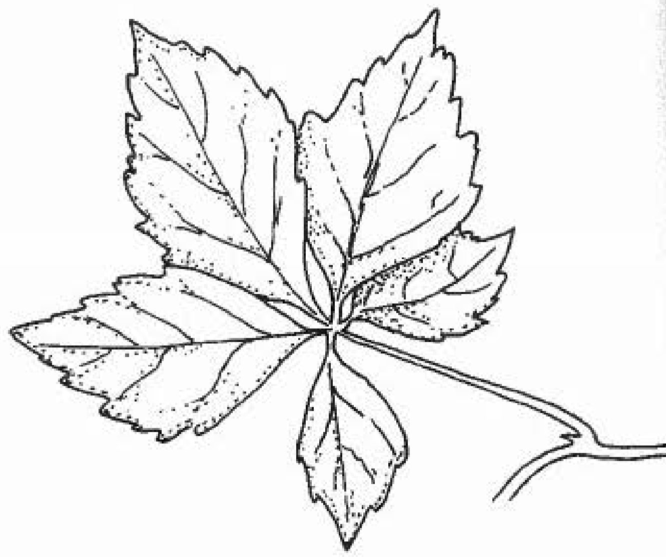


Cissus incisa
Cow-itch vine



Parthenocissus quinquefolia
Virginia creeper

Rhus toxicodendron
Poison ivy

GEOTHERMAL RESOURCES OF BEXAR COUNTY, TEXAS

Duncan Foley
University of Utah Research Institute
Salt Lake City, UT 84108
now at
Department of Earth Sciences
Pacific Lutheran University
Tacoma, WA 98444

C. M. Woodruff, Jr.
Consulting Geologist
P. O. Box 13252
Austin, TX 78711

INTRODUCTION

The Balcones Fault Zone of Central Texas (figure 1) has been recognized as a geothermal area since the 19th century. In the past, the Hot Wells Hotel in San Antonio, the Driskill Hotel in Austin, spas in Marlin, and numerous other sites have used geothermal waters, mainly for bathing. Thermal waters of the Balcones system are currently being used to heat a hospital in Marlin and for aquaculture and agriculture in Corsicana (Blackett and others, 1986). There is even a hot well on the grounds of the State Capitol in Austin.

Through recent programs, funded largely by the U.S. Departments of Energy and Defense, new data have been developed about the thermal regime of the Balcones system. These data provide insight into subsurface hydrodynamic conditions, are important for understanding exploration for geothermal resources, and provide knowledge about constraints on the occurrence of petroleum resources. This report summarizes several previous studies that have not been widely distributed (for complete list, see Woodruff and Gever, 1983), and presents geological, hydrologic, and thermal results from a 1,225 m geothermal well at Lackland Air Force Base in west-central Bexar County.

The U.S. Geological Survey has defined the low-temperature geothermal resource base as those waters that are more than 10°C above the mean annual temperature at a site, but less than 90°C (Reed, 1983). Waters above 90°C are classified as moderate- and high-temperature geothermal (Muffler, 1979). For a well to be considered a resource, Reed (1983) stipulates that it must also have a thermal gradient of at least 25°C/km.

The studies reported herein were initiated as part of a program sponsored by the U.S. Department of Energy to assess low-temperature geothermal resources throughout the nation. The studies along the Balcones Fault Zone are summarized in Woodruff and Gever (1983).

The geology of Bexar County records the history of the Ouachita structural belt, and the influence of a hinge line that developed along the belt on sedimentation, tectonics, and hydrology (Woodruff and Foley, 1985). The Ouachita belt is a foundered Paleozoic orogen. The hinge line separates the stable craton from the downwarping Gulf Coast Basin. The faults of the Balcones Escarpment area (figure 1) developed along the hinge zone. Hydrologic characteristics of aquifers are influenced by these faults (Abbott, 1977).

Geothermics

The temperature at any point in the earth's crust is the product of many factors. These include, but are not limited to, the flux of heat from the mantle, the generation of heat in the crust, proximity to igneous activity, the thermal conductivity of the rocks at the site, local and regional geological and topographic contrasts, and secondary factors such as fluid movement, especially along fault zones. In the Balcones Fault Zone area, few data are available for either the flux of heat from the mantle or the generation of heat in the crust. Until such data are developed, we assume that mantle flux and crustal generation are regionally uniform, although some differences may exist between the Ouachita fold belt and the Gulf Coast basin. The refraction of heat at the boundry between these two geologic provinces has not been assessed as part of this study. No local sources of abnormal heat, such as young volcanic centers, exist in the Balcones Fault Zone area. Extrapolation of data from other areas suggests that the effective overall thermal conductivity of the rock column changes from site to site, depending upon the degree of compaction and the grain size of the sediments. Finer grained sediments will have lower thermal conductivities, and hence higher temperatures. This may have some impact on temperatures in areas with thick shale sequences. These temperature changes are likely to occur over a broad area, rather than being at the local scale at which thermal anomalies along the Balcones apparently occur.

Secondary factors, such as regional and local fluid flow patterns, are probably the dominant control of subsurface temperature.

in Abbott, Patrick L. and Woodruff, C.M., Jr., eds., 1986, **The Balcones Escarpment, Central Texas:** Geological Society of America, p. 145-152

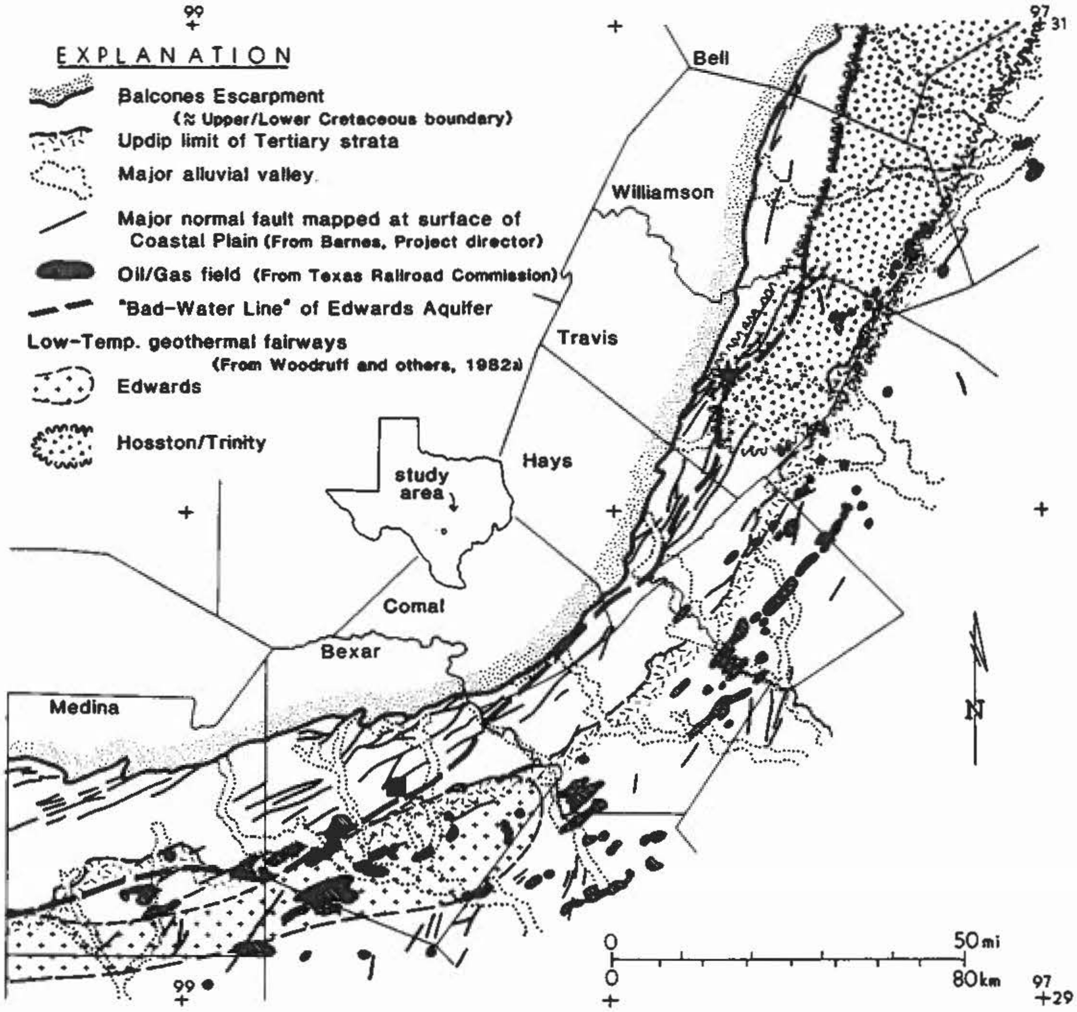


Figure 1. Location of study area, depicting geothermal fairways and the "bad-water line" of the Edwards Limestone. San Antonio is the square in Bexar County. From Woodruff and Foley (1985).

This has been extensively modeled (Smith and Chapman, 1983; Woodbury and Smith, 1985), and described in Tertiary Gulf Coast sediments by Bodner and others (1985). Surficial fluids in recharge zones often generate local cool areas, as the downflowing waters sweep heat out of an area. Upwelling fluids can generate positive thermal anomalies, if they rise quickly enough from depth. Thermal highs, possibly indicating fluid upwelling along growth faults, have been noted in the Wilcox Fault Zone southeast of Bexar County (Bodner and others, 1985).

Thermal gradient data from Bexar County and the surrounding area are depicted in figure 2. Positive anomalies along the Balcones system are local, discontinuous features. Hydrodynamic coupling of fluid and thermal flow, including water movement along faults, can explain the discontinuous pattern of anomalies. Permeable zones with upwelling fluids may be warmer, and zones with downwelling fluids or that are impermeable may be cooler. The localized nature of the anomaly pattern may be caused by areally restricted permeability and fluid flow contrasts, rather than regional changes in the thermal regime of the crust. Abbott (1977) documents extensive movement of water along faults in the Edwards Limestone; such movement could greatly impact local thermal patterns.

GEOTHERMAL RESOURCES AND EXPLORATION IN BEXAR COUNTY

The attractiveness of geothermal resources as an alternative energy resource has led to several projects to define their extent along the Balcones Fault Zone. The discussions below of the Bexar County area are primarily based on data from Woodruff and others (1982a) and Zeisloft and Foley (1983, 1984). The regional concepts are expanded from those in Woodruff and Foley (1985).

Exploration for geothermal resources in Bexar County was driven by the target concept

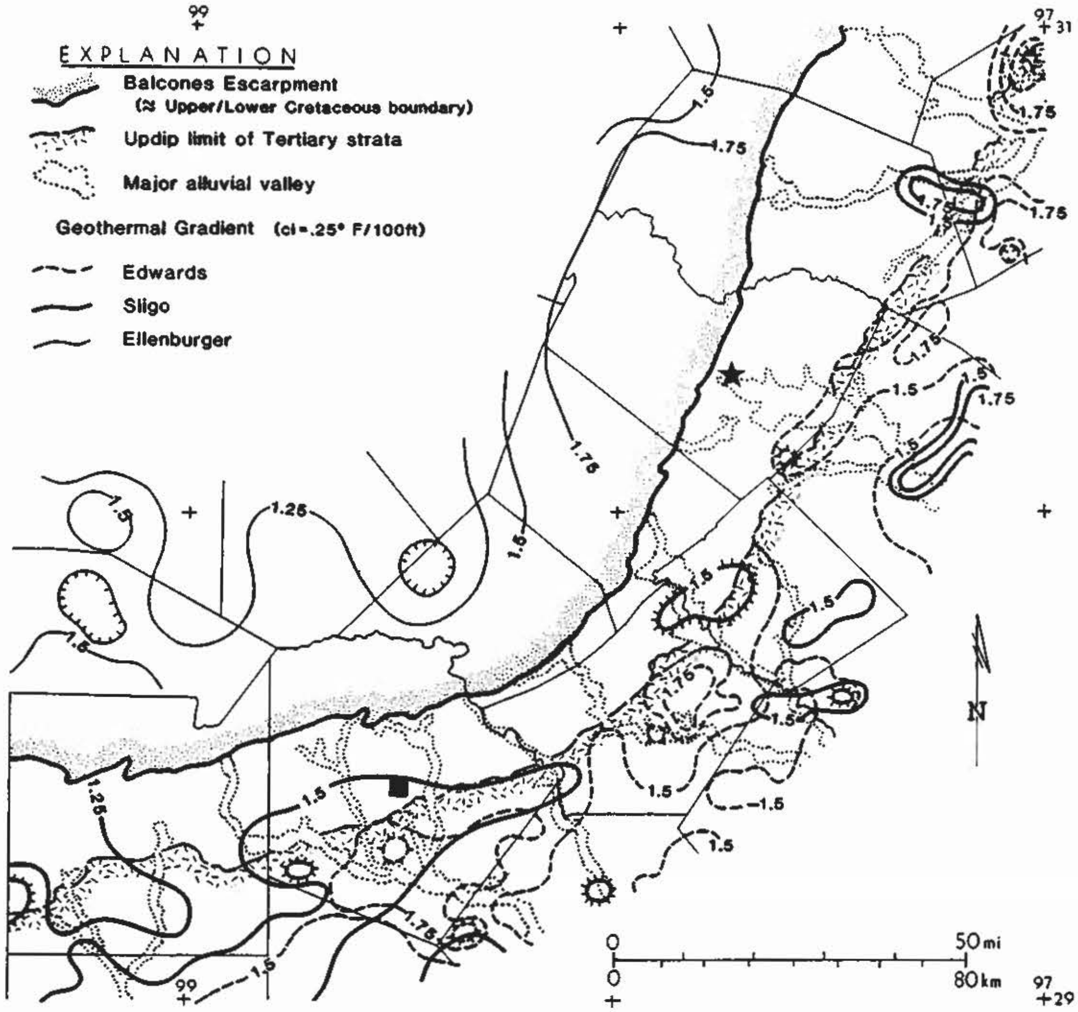


Figure 2. Geothermal gradients in the Edwards and other limestones. From Woodruff and Foley (1985), modified after Woodruff and others (1984).

of seeking zones of upwelling basin brines, where vertical permeability and well performance would be increased by the presence of faults. Data from both water and oil wells were sought to define structural and stratigraphic characteristics of likely reservoir rocks.

The limitations of the regional data base for geothermal interpretations of the subsurface have been described by Woodruff and others (1982b). Two largely exclusive sources of information exist. Shallow aquifers, such as the Edwards and associated units, have much data from water-well drilling and testing, and long-term production records. These data include water temperature, water quality, and productivity characteristics of the aquifers. Deeper aquifers, such as the bad-water zone of the Edwards Limestone and the Hosston Formation, have few data. Data from the deeper units are largely from geophysical logs of oil wells and typically do not include water quality and productivity records. As a result of these limitations, our analysis of geothermal characteristics is based on abundant stratigraphic and structural data, with few reliable geothermal data points.

Fault locations were largely identified from existing geologic maps or interpreted from well data. No seismic data were available for use in this investigation; such data might greatly improve future interpretations of geothermal systems.

Edwards Limestone

Geothermal resources in the Cretaceous Edwards Limestone are restricted to areas south and east of the "bad-water line" (figure 1). This line is located where the aquifer changes from yielding large quantities of cool, cullinary quality water, to yielding irregular amounts of warm but saline fluids. The change in aquifer properties occurs over a short distance, and does not correspond to either fault traces or the strike of the Edwards Limestone or original depositional environments of the limestone (Abbott, 1974). The occurrence of the line changes in depth across the Bexar County, from approximately 150 m in the northeastern portion to greater than 600 m in the southwestern portion. These characteristics led Woodruff and Abbott (1979) to conclude that the "bad-water line" delimits the downdip portion of the Edwards Limestone that is influenced by surface discharge, marking the boundary of the surface hydrologic system with a deeper system dominated by deep basin brines. The line converges near modern springs, suggesting that they represent potentiometric base levels.

The oblique trend of the "bad-water line" with structural trends in the Edwards Limestone is important for the occurrence of geothermal resources. In areas where springs cause a deflection of the "bad-water line" to shallow depths, anomalously warm temperatures are not likely to exist. At greater depths, in areas without such defelctions, higher temperatures may exist in the Edwards Limestone. This is particularily likely to be true where faults allow upwelling of deeper basin brines.

Chemical analyses of waters from the Edwards Formation define three geochemical regimes: fresh, saline and transitional waters. The fresh waters typically have total dissolved solids contents of 350 ppm or less; this contrasts with values of up to 5,000 and from 350 to 3,500 for the saline and transitional zones respectively. Temperatures are less than 30^{o}C in the fresh zone, and often more than 40^{o}C in the saline zone. Major chemical species are also different. Fresh waters are dominately Ca-Mg-HCO_3 and saline waters are Na-Cl-SO_4. Details of the origin of chemical constituents in the Edwards Limestone waters are not resolved (Land and Prezbindowski, 1985; Stoessell and Moore, 1983; 1985). Current models agree, however, that updip movement of fluids from the Gulf Basin is an important process. Transition zone waters are usually intermediate in both temperature and water chemistry. The contact between fresh and saline waters in many areas is abrupt, and extends to depth.

The boundary between fresh and saline waters in the transition zone has migrated with time, probably as a response to drought and recovery periods. During drought, artesian pressure and water levels drop, and saline fluids move updip. In recovery, increased pressure from fresh waters pushed saline fluids to greater depth (Garza, 1962).

Temperatures in the Edwards Limestone (figure 3) increase both laterally and with depth. The lateral increase is most marked at the change from fresh to saline water. The increase of temperature with depth is typically gradual.

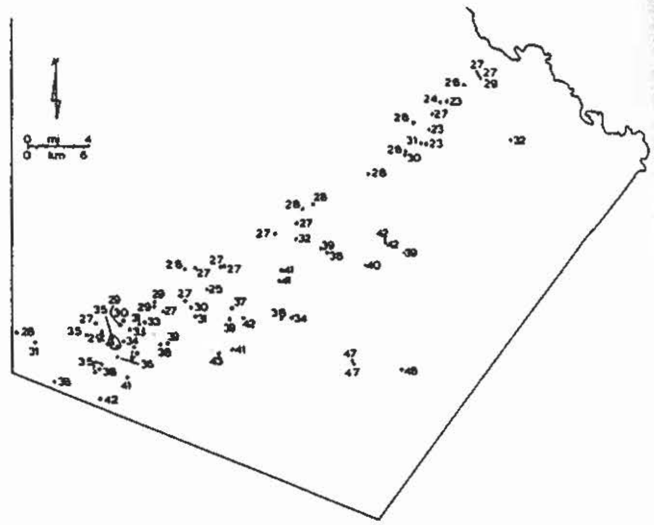


Figure 3. Temperatures from wells in the Edwards Limestone, in degrees C. See Woodruff and others (1982b) for further data.

The transition zone is geothermally important. It provides areas where relatively fresh fluids are apparently heated by upwelling saline solutions. Temperatures of 40^{o}C and dissolved solids contents of less than 1,000 ppm may locally be obtained.

Hosston Formation

The Hosston Formation is the lowermost Cretaceous unit in central Texas (Bebout and others, 1981). It is deposited either on Ouachita metamorphic rocks or on sediments deposited in grabens in the metamorphic rocks. Flawn and others (1961) document nearly 800 m of unmetamorphosed sediments in a well immediately south of Lackland Air Force Base. The geothermal well drilled on the base, which is discussed below, encountered sandy red beds beneath the Hosston.

The Hosston was deposited in both fluvial and marine environments in Bexar County. In the northwestern part of the county, where the Ouachita rocks are relatively shallow, the Hosston is composed of dip-oriented river and delta deposits (Woodruff and others, 1982b). Beneath the southeastern portions of the county, marine, strike-oriented beds dominate. The Hosston also includes dolomites in some areas (Bebout and others, 1981). Formation and sand thicknesses increase from north to south across Bexar County (figure 4). The elevation of the Hosston also changes dramatically across the county, from at or near sea level in the north to more than 1.6 km below sea level in the south.

Woodruff and others (1982b) noted the potential for geothermal resources in the Hosston Formation, and Woodruff and others

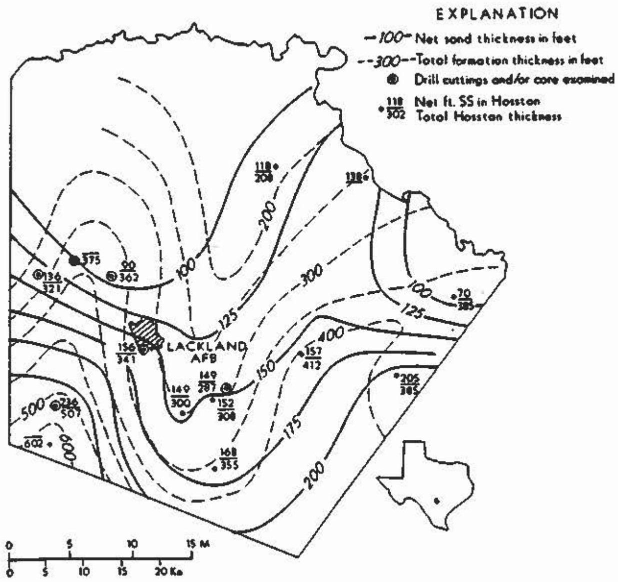


Figure 4. Hosston Formation isopach map, Bexar County. From Zeisloft and Foley, (1983).

(1982a) depicted the area of Bexar County they felt most likely to have such resources. Sorey and others (1983), using different criteria than Woodruff and others (1982a; 1982b) to define geothermal resources, identified five counties along the Balcones Fault Zone that had resources in the Hosston Formation and equivalent units. Bexar County was not among these.

The choice of the Hosston Formation as a target unit for detailed geothermal exploration at Lackland Air Force Base was based upon the potential production characteristics of the rocks, which were known geothermal producers in the cities of Marlin and Corsicana, and upon the stratigraphic position of the Hosston as the basal and therefore warmest sand overlying basement rocks.

Woodruff and others (1982b) suggest that the different environments probably have major impacts on hydrodynamic and geothermal properties of the formation. Dip-oriented sands allow recharge waters to circulate down. This may allow ground water to remain relatively fresh and cool at moderate depths. Strike-oriented sands, however, provide no continuity for downward circulating waters, and may contain residual brackish fluids. These conditions suggest that, in general, fresher and slightly cooler fluids will be found in the dip-oriented sands, and warmer, more brackish waters will occur in the strike-oriented units. The Hosston, in a manner analogous to the overlying Edwards Formation, should have a mixing zone between the two units.

Lackland Air Force Base

The U.S. Air Force funded a program to site and drill a geothermal test well at Lackland Air Force Base (Zeisloft and Foley, 1983; 1984; Foley and others, 1984). Lackland AFB is located in west-central Bexar County; the base overlies several faults of the Balcones Fault Zone. The Hosston Formation was chosen as the target, owing to its known geothermal productivity in north-central Texas, and its position as the deepest and presumably warmest unit. Stratigraphic, hydrologic, and thermal data were obtained from the test well drilled in 1983. Normal regional stratigraphy was encountered, with a red bed sequence (Triassic graben fill?) occurring beneath the Hosston Formation. Preliminary hydrologic data suggest moderate productivity may be expected, but water temperatures beneath the base are not anomalously warm (42°C).

Stratigraphy of the well is illustrated in figure 5. No apparent faults were noted in either the cuttings or well log data and no major zones of lost circulation were present. The basal red bed sequence is presumed to be equivalent to similar units encountered in several other wells in the area (Flawn and others, 1961).

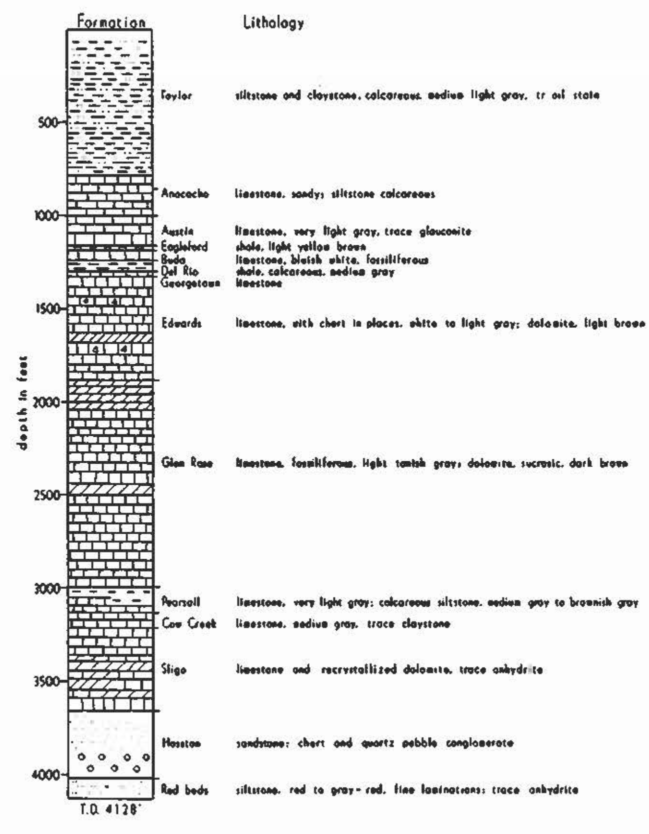


Figure 5. Lithologic log, Lackland Air Force Base #1. From Zeisloft and Foley (1984).

Sidewall cores were collected as part of the lithologic analysis program. Data from these cores do not indicate the presence of commercial quantities of oil or gas. No major shows were encountered, despite drilling through zones that are either productive or the focus of exploration activity nearby. Porosity ranges from 14 to 24 percent in sand-rich beds; permeability ranges from less than four to nearly 80 millidarcys.

Hydrologic testing consisted of short term air lifts. No long term tests have been made on the well. The data were analyzed by Dr. David Allman of EG&G Idaho, Inc., under Air Force funding. Dr. Allman's unpublished interpretations indicate that the Hosston Formation has a specific capacity of 2.32 gpm/ft. He calculated a transmissivity of 3800 gpd/ft, assuming a storage coefficient of 1 x 10E-4.

Water samples were collected during the air lift testing. Results of the analyses are presented in table 1. These samples might be slightly contaminated with drilling fluid, but the data are very similar to analyses reported by MacPherson (1982) for thermal fluids in Hosston-equivalent units in north-central Texas. These waters are probably from the transition zone between presumed fresher waters to the north and more saline waters to the south. They have moderate total dissolved solids and relatively high sulphate.

Geothermometer calculations to estimate possible deep reservoir temperatures suggest that the fluids may have equilibrated with rocks at about 60°C (Zeisloft and Foley, 1984). It must be noted, however, that geothermometers are probably unreliable in this temperature range.

Dr. David Blackwell of Southern Methodist University obtained a high-precision thermal log of the well approximatly three months after drilling. The well had been shut in between air lift testing and the thermal logging. The results of the thermal logs are presented in figure 6. The maximum temperature encountered was slightly more than 42°C. This compares closely with the maximum temperature measured during the air lift test of approximately 41°C. The thermal gradient of the well is relatively low, at approximately 15°C/km.

Results of the drilling at Lackland suggest that the Hosston Formation beneith the base is probably in the hydrodynamic mixing zone. Relatively cool temperatures probably occur in the vicinity of the well, and are related to downwelling fluids. The moderate total dissolved solids of the waters, however, suggests that some influence from upward moving deep basin brines is also present.

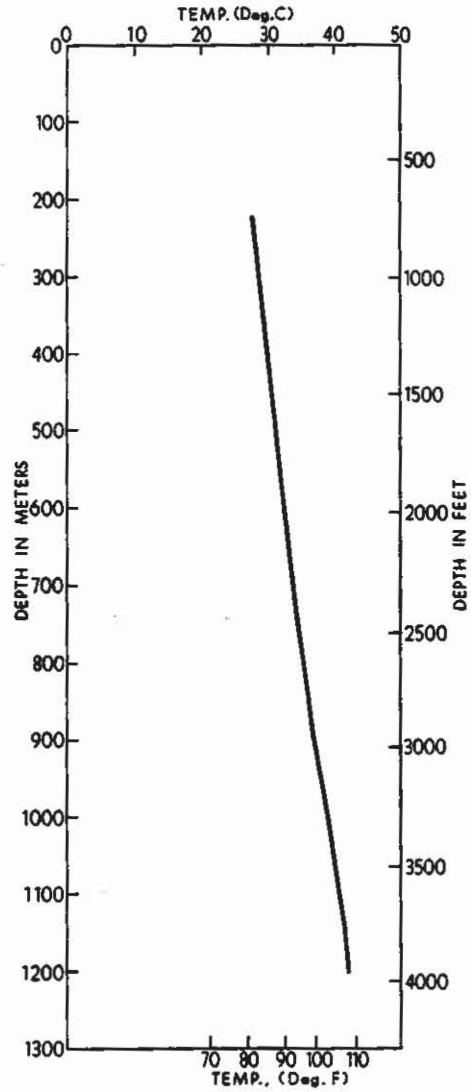


Figure 6. Thermal log, Lackland Air Force Base #1. From Zeisloft and Foley (1984).

TABLE 1
Lackland AFB #1 representative water analysis

concentrations in ppm

Element	Concentration
Na	561
K	43
Ca	109
Mg	35
SiO2	20
B	1.0
Li	0.45
Sr	5.2
HCO3	338
SO4	646
Cl	524
F	2.3
TDS(meas.)	2218

Sample 3 in Zeisloft and Foley (1984). For sampling and analytic details, consult that source.

CONCLUSIONS

Regional groundwater flow is an important geologic process in the generation of geothermal systems (Sorey and others, 1983), the creation of ore deposits (Bethke, 1986), and petroleum migration and trapping (Jones, 1984). All three processes are probably taking place currently along the Balcones Fault Zone area. Bodner and others (1985) noted these processes in Gulf Coast sediments south of Bexar County.

The association of high thermal gradients and warm waters with saline fluids typical of oil fields suggests a correlation of geothermal resources with upwelling Gulf Basin brines. The discontinuous pattern of thermal anomalies suggests that local controls, such as hydrodynamic movement, may be an important factor in controlling the location of anomalies. The Balcones Fault Zone provides an area of increased vertical permeability, which may allow the deeper fluids to reach the surface.

Future exploration for geothermal resources along the Balcones area will need to include the possibility that faults can also provide channels for downmoving waters, as may be the case near Lackland Air Force Base. These cooler fluids can create zones where geothermal resources are not likely to exist at depth. Determination of zones with down- or up-moving fluids is complicated by an often unreliable data base and the apparently relatively rapid areal changes in thermal conditions. It is possible that the radius of influence of a thermal data point along the Balcones may be less that two or three kilometers; this need to be studied in more detail.

Basin hydrodynamics has long been recognized as an important contributing factor to the generation of Mississippi Valley type stratiform ore deposits. A recent synthesis of the role of hydrodynamics in ore formation is presented by Bethke (1986). The generation of ore deposits in Texas is currently poorly documented, but high lead concentrations were documented by Prezbindowski (1981) in the bad-water zone of the Edwards Limestone in the inner Gulf Coast.

The association of oil fields with thermal highs, and the probable role of water as a driving mechanism in both movement of oil and generation of thermal highs was first noted in Texas by Plummer and Sargent (1931). This phenomena has since been documented in many other areas (e.g. Meyer and McGee, 1985; Zielinski and Bruchhausen, 1983). A relationship of thermal highs with petroleum resource accumulations may exist along the Balcones Fault Zone (Woodruff and Foley, 1985), and could provide a valuable tool in petroleum exploration.

ACKNOWLEDGEMENTS

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LAND USE AND CULTURAL CHANGE ALONG THE BALCONES ESCARPMENT: 1718-1986

E. Charles Palmer
Texas Natural Resources Information System
P.O. Box 13231, Capitol Station
Austin, Texas 78711

ABSTRACT

Since earliest European settlement, the Balcones Escarpment has stood as a cultural frontier, a dividing line between east and west, between the farming economy of the coastal plain and the ranching economy of the Texas Hill Country. The Escarpment has greatly influenced the cultural development in the land which it transects. The following narrative traces the evolving land use and the changing cultural landscape along both sides of the Escarpment from the 18th century Spanish/Mexican settlement of the San Antonio area and the 19th century German colonization of the Texas Hill Country, through the major trends of the current century, and finally, to the boom and decline of the 1980's.

EARLY SETTLEMENT

The Spanish/Mexican Period: 1718-1836

As part of Spain's Internal Provinces, the area which is now Central Texas remained virtually unknown and unsettled by the "civilized" world until well into the eighteenth century. It was too remote from Mexico's population centers to justify efforts at colonization, and early expeditions in search of mineral wealth, although they inspired extraordinary feats of endurance, had generally failed.

Earliest permanent Spanish settlement in Texas began in 1718 at the site of present day San Antonio with the founding of the Mission San Antonio de Valero, later known as the Alamo. Several additional missions were soon established, all downstream from San Pedro Springs, which supplied the mission compounds and agricultural fields with water through an extensive system of canals known as asequias. This seemingly endless and reliable source of water issuing as artesian springs from the base of the Balcones Escarpment was the principle reason for selecting the sites for the early missions. The artesian springs have been the lifeblood of San Antonio from its very inception. Many of the original irrigation canals served the missions until they were abandoned in the early 19th century, and then continued to provide water to local fields well into the twentieth century. Remnants of the original canal system can be seen to the present day along with a section of a still-functioning Spanish Aqueduct. There is no better reminder of the historic importance of the springs for the development of San Antonio. The city was founded because of the springs, owed its development to the reliable artesian water supply and has the distinction today of being the largest city in the world whose water needs are supplied entirely by groundwater.

San Antonio was established primarily as a mission outpost in Spain's Internal Provinces and served as a link between the population centers to the south and the even more remote East Texas missions. Numerous roads, including the King's Highway or Camino Real either originated at San Pedro Springs or passed by the Springs using them as a convenient stopping place.

Throughout the Spanish period and for the first several decades of Mexican sovereignty (beginning in 1810) the area along the Balcones Escarpment remained sparsely populated. The Camino Real, blazed in 1691, extended northward from San Antonio's San Pedro Springs along the base of the Escarpment past the site of present-day New Braunfels where its travelers could replenish water supplies from the Comal Springs before proceeding eastward to the Spanish Missions at Nacogdoches. A mission named Nuestra Senora de Guadalupe was constructed in 1757 near Comal Springs and served as a stopover along the route. It was later abandoned, and by mid-nineteenth century all traces of it had disappeared. Fifteen miles farther north along the Camino Real, at the site of present-day San Marcos, another short-lived Spanish Mission, the San Xavier, was established in 1755 and also endured only one year.

The failure of Spain, and later of Mexico, to populate the Central Texas region and thereby safeguard it against outside incursions, is understandable considering the remoteness of the region and the long distances to supply centers. By the year 1821, when the granting of land for Moses Austin's colony opened the gate for immigration from the United States, there were still no settlements of note north of San Antonio.

The Early Anglo Period: 1830-1844

By 1830 the English-speaking whites residing in Texas outnumbered the Mexicans by three to one. The population was almost entirely rural, centered in the Brazos and Colorado River bottoms. Settlement along the eastern margin of the Balcones Escarpment did not begin in earnest until after the Texas Revolution of 1836.

The present site of Austin, originally called Waterloo, was settled gradually in the mid 1830's. The site was favorable for a permanent settlement because of the reliable water supply of the Colorado River which descended from the higher county to the northwest. In addition, artesian springs provided an early source of power for milling operations and

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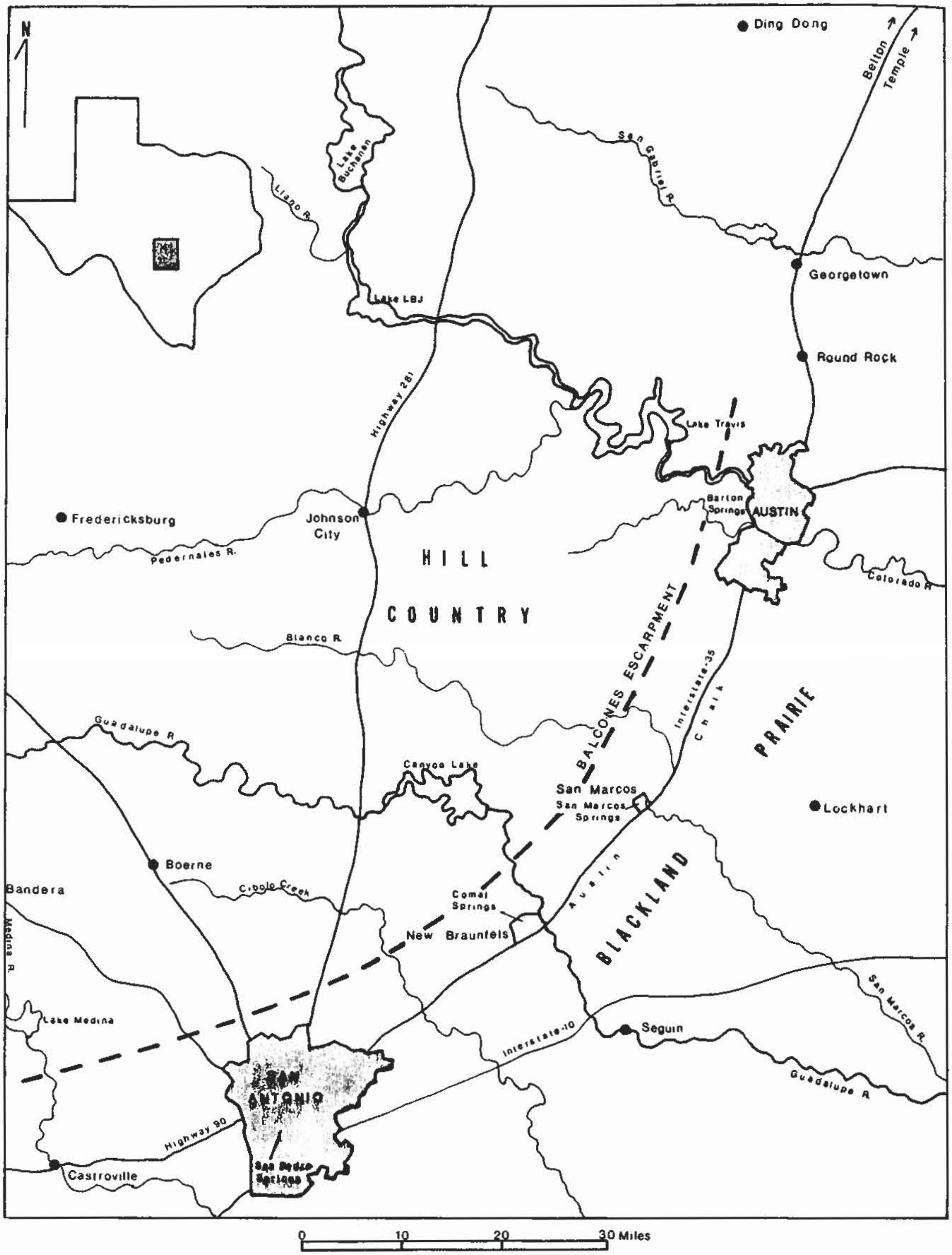

Figure 1. Central Texas And The Balcones Escarpment

recreation. The site offered the further advantage of fine farmland immediately to the east and grazing land in the hills to the west. The town itself was located on a relatively firm limestone and chalk base offering an abundance of building material.

Artesian springs rising from the base of the Escarpment were influential in the siting not only of San Antonio and Austin, but of other towns such as New Braunfels in 1844, San Marcos in 1847, Georgetown in 1848, Belton in 1850, and Bracketteville in 1852. Water power from the springs and from the rivers which flowed eastward from the Hill Country, provided a necessary power source for the early settlements. By 1861, for example, the town of New Braunfels had a flour mill, four grist mills and two saw mills, all of them water powered (Benjamin, 1974, 70). Although there was never a clear-cut "break in bulk" point along most Texas rivers, as there was along the fall line of the eastern seaboard, the shoals and rapids beginning just below the escarpment interrupted river transport and offered an added incentive for locating settlements at those points. The site for Austin was chosen at the fall line of the Colorado, and although navigation downstream was finally abandoned, it was originally considered to be of great importance for the town's future development.

A number of early towns were founded on the Austin Chalk, a narrow exposure running about 500 miles generally northeast-southwest from near Sherman in North Central Texas to south of San Antonio, closely paralleling the Balcones Escarpment. The Austin Chalk provided good building material and a somewhat higher altitude than the black lands immediately to the east. It was well drained and close to good cultivable farmland. Furthermore, it provided a ready supply of serviceable building material. Towns originally settled on the Austin Chalk include Temple, Austin, San Marcos, New Braunfels and San Antonio.

The Balcones Escarpment has also influenced transportation patterns. The Camino Real skirted the Escarpment between San Antonio and the San Marcos area before veering eastward toward Nacogdoches. The slightly higher and better-drained terrain provided sound footing for oxcarts and wagons even during rainy periods which made the Blackland Prairie soils virtually impassable. Transportation routes connecting the early towns evolved naturally -- first wagon roads and stagecoah routes, then railroads, and finally modern highways. The present-day Interstate Highway-35 follows part of the route of the original Camino Real. A portion of the Chisholm Trail was blazed along the same route.

German Settlement of the Hill Country: 1844-1900

As of the early 1840's the land west of the Escarpment remained free of European influence. It was the undisputed realm of the Comanches, Apaches, and several lesser tribes. An early Spanish mission near the present-day town of San Saba was founded in 1757 and abandoned in 1758. Early Anglo settlers had little interest in the shallow, Hill Country soils. When Ferdinand Roemer vistited the Hill Country west of New Braunfels in the mid 1840's he found no Anglo habitation from New Braunfels to Fredericksburg. Ten years later, Frederick Law Olmsted noted in his travel log that the area was dotted with farmsteads.

Settlement of the Texas Hill Country began in the early 1840's and moved from east to west. A number of ethnic groups were involved. For example, in 1843 a group of Alsatians founded the town of Castroville about twenty miles west of San Antonio. By far the most influential ethnic group, however, was the Germans. Their settlement patterns, house types, and language dominated the Hill Country during the latter half of the nineteenth century and are important elements of the local culture to the present day.

Scattered German settlement had occurred in Central Texas in the early years of the century, but it was the founding of New Braunfels in 1844 that set the scene for large-scale German immigration. New Braunfels was founded by the German nobleman Prince Carl of Solms, who named the new settlement for his town of origin, Braunfels on the Lahn River in Germany. He had been appointed by a German emigration society to establish a German colony in Texas and to be responsible for its prosperity. The original group of colonists arrived on the Texas coast in 1842 and made their way inland to the present location of New Braunfels. The site was expected to be temporary, to serve only until legal problems regarding the intended destination farther west could be settled. The New Braunfels site proved favorable, however, with unfailing artesian springs and abundant farmland; the colony thrived.

The plan of settlement for New Braunfels was for each family to have a lot of about one half acre in town and ten acres of cultivable land within easy walking distance. The yeoman farmers were to live in town and work their nearby lands. This nuclear village/farm concept broke down within a few years with the increasing population; cultivable land within easy walking distance of the town was spoken for, so new arrivals began looking farther afield for farmlands. The fertile alluvial valleys in the hills to the west were soon occupied.

The founding of Fredericksburg in 1846, about sixty miles west of New Braunfels, opened up a new trade route through the Hill Country and encouraged new settlements along the way. Most of the new settlement clusters never became towns; they typically consisted of a few houses, perhaps a store, and eventually a church. With succeeding generations, many of these communities developed into extended family clusters with each succeeding generation occupying a dwelling on the same property. This became a very charactertistic pattern on the German Hill Country landscape of the mid-nineteenth century, and is in evidence even to the present day.

The most distinctive remaining signs of the early German settlement period are the typical fences, many of which are still in use. But the original German fences were not of stone, instead they were of cedar or oak, usually laid out in a zig-zag pattern (Jordan, 1964, 163). By the late 1850's the Germans began building stone fences to enclose not only house and gardens, but pastures and entire land holdings as well. German families labored for months or even years to complete large fencing jobs. By contrast, early non-German settlers generally preferred the open range and were less likely to fence their holdings. This was undoubtedly one of the factors which helped establish the prosperity of the German farmer, particularly with the end of the open range. When barbed wire was introduced in the 1880's, stone fencing became obsolete, but the existing stone fences endured, and many miles of them remain in use to the present day.

The original German dwellings were log huts, but these were soon replaced by more traditional German stone work, plastering and half timbering. (Jordan, 1964, 165-166). Many of these nineteenth century buildings are still in daily use and are quite picturesque. Others have been veneered and remodeled to the point of being recognizable only on close inspection. The extremely wide hallway of an old one-story cottage may have been the dog trot of a nineteenth-century German farmhouse.

The growth of New Braunfels and Fredericksburg encouraged further penetration into the Hill Country. The town of Bandera was originally settled by a group of shingle makers attracted to the area by the stands of virgin cypress along the Medina River. The settlement was expanded in 1855 by the arrival of a group of Polish immigrant families who worked in the saw mills and shingle factories (Coleman, 1963, p. 23). The shingles were hauled by ox cart to market in the city of San Antonio. Thus, many of the largest of the accessible cypress trees in the Hill Country were cut in the mid-nineteenth century. An occasional slowly decaying stump from these early giants attests to their size.

In 1854 a group of 250 Mormons from Nauvoo, Illinois established the Village of Mountain Valley in the area currently inundated by Lake Medina. The Mormon colony prospered initially, but after a few years it disbanded, apparently owing to problems with the Indians. Most of the Mormons either continued south to Mexico or returned to the midwest. A few settled in or around Bandera.

The Civil War temporarily halted immigration and the lack of military protection on the frontier impeded settlement in the Hill Country, but by the 1870's the pace had quickened. The introduction of windmills in the 1880's opened the fertile alluvial areas in the more remote regions (Schmid, 1969, p. 40). Cattle and sheep raising flourished both on the open range and within the fenced pastures. Sheep raising had become important even before the Civil War and by the 1870's there were an estimated 30,000-40,000 head in the vicinity of Boerne alone (Krueger, 1929, p. 186). During the last decades of the century sheep raising surpassed cattle raising in importance, and individual herds numbering in the thousands were common.

Goat raising began in the Hill Country in the mid 1850's, and the Angora goat was introduced in 1858 (Jordan, 1964, p. 158). Goat raising remained a relatively small-scale occupation, however, until well into the twentieth century. By that time the effects of overgrazing, mainly by sheep, had become obvious and goat raising was a logical alternative. It has remained so to the present day.

By the last years of the nineteenth century, both the Blackland Prairie and the Hill Country showed the effects of misuse of the land. The Blackland Prairie soils, once considered among the best in the nation for cotton, had long since declined and required heavy applications of chemical fertilizers to produce acceptable crops. In the hills to the west, overgrazing had contributed to erosion and decline in fertility, in some areas transforming grasslands into barren lands. Overgrazing and browsing had so improverished the habitat of the whitetail deer that by the turn of the century they were rarely seen.

TWENTIETH CENTURY TRENDS

Agricultural Land Use

The early years of the current century witnessed continued overgrazing, particularly by sheep, and intensive browsing by the ever-increasing goat herds. The "goat line" or browse line, characterized by the removal of green vegetation up to a height of about six feet, became a familiar sight. The declining grass cover and its replacement by woody plants was generally attributed to this overstocking.

After the Second World War the Federal Goverment began to take an active role in encouraging more informed land management practices. Soil conservation districts were organized under the supervision of the U.S. Deparment of Agriculture. Since that time, conservation officers have worked with farmers and ranchers to reintroduce favorable grass species, avoid overgrazing, promote brush clearing, and prevent soil erosion. Among the recommended conservation practices is the clearing of cedar trees to encourage the growth of grasses and to allow unrestricted growth of live oaks. Unfortunately, many Hill Country ranches which have been carefully cleared of cedar, are now losing their live oaks to a fungal disease known as live oak wilt which has affected live oak trees in a large area of Central Texas.

By the 1980's livestock raising was still the dominant agricultural land use in the Hill Country, accounting for over 90% of all agricultural income. Commercial agricultural crops were primarily sorghum, wheat, oats, and hay.

In contrast to the Hill Country, agriculture along the downthrown side of the Escarpment has seen a sharp evolution over the years. Cotton, once the mainstay of Blackland Prairie agriculture, has given way to more diversified cropping including corn, sorghum, wheat and hay. In recent years the strong trend has been away from row crops altogether and toward improved pasture and cattle raising.

Non-Agricultural Land Use

Much of the Hill Country landscape could be classified as recreation land. The whitetail deer population has increased dramatically thanks to conservation measures, the near eradication of the screworm, and to the increase in brush cover. Deer hunting has become an important factor in the economy with many ranchers depending more on revenue from deer leases than from any other source. Yearly harvesting is necessary to prevent winter dieoffs owing to insufficient forage.

A recent addition to the Hill Country landscape is the eight-foot-high wire fencing designed to contain exotic game animals imported by local ranchers. Importation of exotics, principally ungulates, began on the King Ranch in the 1930's. At the present time it is estimated that over 55,000 exotics roam the state, a large percentage of them in the Hill Country (Doughty, 1976). Axis deer and mouflon-barbados sheep are probably the most numerous, but others including black buck, nilgai antelope, and aoudad sheep are also found in large numbers (Doughty, 1976; Ramsey, 1976). Russian boars have become dangerous pests in parts of the Hill Country. Many landowners raise exotic deer and antelope in large pastures surrounded by high fences and receive handsome fees from hunters in return for guaranteed trophies. The ecological effects of the thousands of exotics that have gone wild is the subject of considerable controversy among ecologists. A few of the exotics adapt so well to their new environment that some ecologists predict that they may actually become dominant species during the coming century. A hunter on a Hill Country "non-exotic" deer lease reported his 1986 kill as one axis deer, one Russian boar, and one whitetailed deer.

There are a number of well established state and private parks in the Hill Country and others are planned. Several extensive caverns have been opened to the public. Dude ranches have become especially popular for vacationers from the cities. Bandera's claim to being the "Cowboy Capitol of the World" may be doubtful, but its distinction as the dude ranch capitol of Texas is unquestioned.

The trend in land ownership is toward disaggregating the larger holdings into 10-20 acre tracts for sale as weekend retreats. High land prices are making it noneconomical for many farmers and ranchers to continue in agriculture.

The trend toward recreational land use has quickened with the increasing popularity of canoeing and tubing in the local rivers. The Guadalupe has been noticeably affected both above and below Canyon Lake. Land parcels as narrow as thirty feet have been sold along the Guadalupe for cabin sites, tube rental establishments, and concessions (Palmer and others, 1984). The increasingly heavy use of the area is putting a strain on transportation and other facilities, and taxing the patience of longtime residents who are faced with ever higher taxes and the residue of beer cans and broken glass left by weekend revelers. The challenge to planners is to make the attractions of the area available to the public while maintaining the integrity of the environment. Effects on the Edwards Aquifer have not been determined but also are cause for concern.

THE AUSTIN-SAN ANTONIO GROWTH CORRIDOR

Silicon Prairie

The economic life of Austin, the state capital, has traditionally been centered on state government and The University of Texas. For decades, Austinites have taken pride in the city's clean air, lack of heavy industry, manageable traffic, and Barton Springs swimming pool, a 1000-foot long oasis fed by artesian springs from the Edwards Aquifer. The economy of San Antonio, on the other hand, has been based on federal government employment; the city's five military bases employ over 43,000 persons. Like Austin, San Antonio has relatively little heavy industry. It has customarily been regarded as a picturesque, slow-paced tourist center featuring historic Spanish missions and lush parklands. The seventy-five mile corridor connecting the two cities has been little developed with only two significant population centers, San Marcos and New Braunfels. The only major industries along the corridor until recent years were several limestone quarries. Such was the Austin-San Antonio corridor prior to the 1970's.

Development of the corridor can be attributed, first, to the booming Texas economy during the late 1970's and early 1980's at a time when most of the nation was experiencing an economic recession. High crude oil prices favored all aspects of the state's economy. Low-yield areas which had never before been seriously explored or exploited, such as parts of the Austin Chalk, became the sites of frantic activity, and sleepy Black Prairie towns such as Lockhart and Seguin became centers of a mini oil rush. State budget surpluses were counted in the billions of dollars. The result was an influx of people as well as new and relocated industry. Texas experienced a 1970-1980 population increase of twenty-seven percent, one of the highest in the nation. John Naisbitt predicted in his 1982 bestseller, Megatrends, that Austin and San Antonio would be among the top ten growth areas in the nation at least to the end of the century.

The Austin-San Antonio corridor offers several attractions for prospective businesses and industry. Climate and environment are considered favorable. Spring-fed streams and swimming pools, clear Hill Country rivers, and the scenic Hill Country itself, are important drawing cards. Compared to many other states, wages are low; the area is not heavily unionized, and it has an adequate labor force. The cost of living has been relatively low (this has changed dramatically in Austin since the early 1980's). And very importantly, major universities, particularly The University of Texas at Austin and The University of Texas at San Antonio, with established graduate programs in the sciences and engineering, are attractive to high-tech industry.

Along with its advantages, however, the corridor has certain drawbacks which may prevent it from attaining the high goals which its promoters hold for it. Clearly, it is not in a central location relative to the nation's major industrial and population centers. Distance from raw materials and lack of a seaport could be deterrents to some types of industry. But the corridor's greatest disadvantage is the fact that it exists in a state which is so tied to the petroleum industry that a downturn in that sector affects the entire economy. All support facilities on which a new industry would depend are affected: university research budgets, opportunities for spouse employment and many of the other factors which make the area so attractive. This consideration, however, seemed remote when the price of crude oil was $40 per barrel.

Efforts to attract high-tech industry to the Austin-San Antonio Corridor have been well-planned and coordinated. California's Silicon Valley and, less frequently, North Carolina's Research Triangle, are mentioned as models. The Texas Business Review recently noted that "Austin and San Antonio are regarded as being at opposite ends of a 75-mile corridor along I-35 that will become a sort of silicon prairie" (Texas Business Review, July 1984). City officials of both San Antonio and

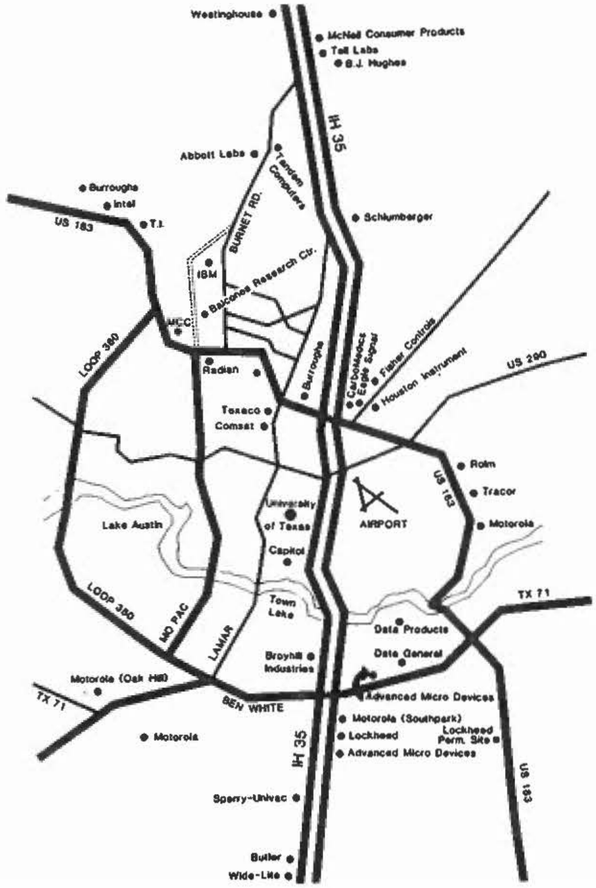

Figure 2. High Tech Employers In Austin

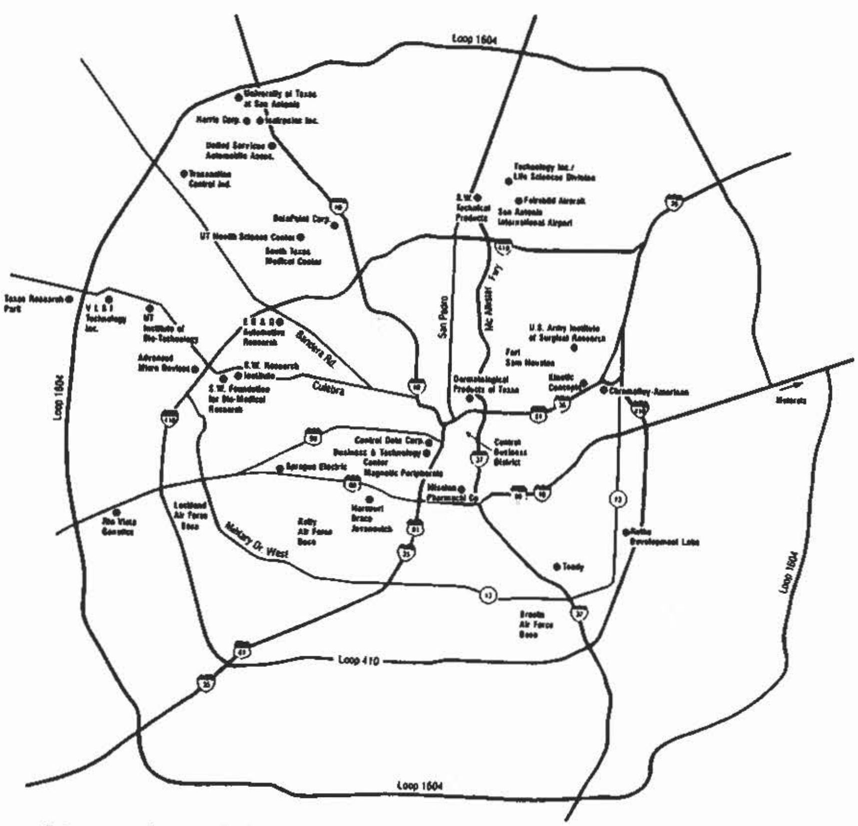

Figure 3. High Tech Employers In San Antonio

Austin have worked closely with state government as well as with The University of Texas System to promote the area and provide inducements to high-tech industry.

Several high-tech companies, including Tracor, IBM, and Texas Instruments were established in the Austin area prior to the 1970's, and a number of similar industries were attracted during the decade of the 70's. But it was the selection of an Austin site by Microelectronics and Computer Technology Corporation (MCC) in 1983 that marked the height of achievement by the corridor promoters. MCC selected Austin over dozens of other potential sites only after coordinated inducements from the City of Austin, the Governor of Texas, H. Ross Perot, and The University of Texas. The expectation was that the relocation of MCC to Austin would begin a mass influx of similar high-tech firms to the area.

To promote and direct the expected growth, San Antonio's Mayor Henry Cisneros and others formed the Greater Austin-San Antonio Corridor Council. Alternative scenarios for future growth, blueprints for expanded airports, proposals for a fast rail system along the corridor and talk of future super highways became daily fare in the local newspapers.

As of February 1985, 40% of Austin's non-government work force was employed in the high-tech area -- twice the percentage so employed in Dallas and seven times that in Houston. Some of the high-tech firms which had located in Austin by the summer of 1986 are listed in Table 1.

Table 1

FIRM	EMPLOYEES
IBM	7000
Texas Instruments	3500
Lockheed	2500
Motorola	5800
Advanced Micro Devices	1400
Abbot Labs	1000
Tandem Computer	250
MCC	350

San Antonio has been somewhat slower than Austin in attracting high-tech industry. With less university influence, and a generally lower wage scale, San Antonio is more oriented toward traditional assembly-type industry. The goal of Mayor Cisneros and other city leaders, therefore, is to make San Antonio a center, not of high-tech research, but of high-tech manufacturing. The intent is to build on existing strengths, particularly in the field of biotechnology. The extensive medical facilities of South Texas Medical Center, the medical orientation of several of the military bases including Brook Army Medical Center, and several biomedical research firms, create a favorable climate for this type of development. Among the installations currently on the drawing boards is the 1500-acre "Texas Research Park," a biomedical research park which will house the Southwestern Foundation for Biomedical Research and The University of Texas Institute of Biotechnology.

Land Rush

With the influx of high-tech industry and general growth of the economy, there has been a land rush of unprecedented proportions. Rural as well as urban land in the entire Austin-San Antonio Corridor began increasing rapidly in the mid '70's, and by the early '80's, the rate of increase was truly surprising. After relocation of MCC in the hills northwest of Austin in 1983 land prices in that immediate area doubled and tripled overnight.

The price of prairie land east of the Escarpment increased less rapidly. One stark exception, however, was land east of Austin near the proposed site for a new airport. Speculation land was purchased and "flipped" within days for 100% profit or more. Tracts which sold for $1300-$1500 per acre in the late 1970's were suddenly selling for $6000 and more in 1984.

Over the years there has evolved a definite change in perception toward prairie land on the one hand and Hill Country land on the other. From earliest agricultural settlement, rich Blackland Prairie land was preferred over the rocky Hill Country. Although there had long been scattered ranches in the Hill Country, it was generally considered most suitable for "cedar choppers," most of whom squatted on the land and made their living by cutting cedar for fence posts. The demand in recent years, however, has been for non-agricultural land, for a weekend retreat, or for a suburban lot with a view. Hill Country land, unproductive from an agricultural perspective, has replaced the fertile blacklands as the high-dollar location in Texas real estate.

The following scenario has been repeated innumerable times in recent years: in the early 1950's a family bought 300 acres of Hill Country land about fifteen miles northwest of downtown Austin. It was cheap, unfit for agriculture, suitable only for a few goats, secluded weekends, and church retreats. The few neighbors were squatters who looked after the place during the week with the unspoken understanding that they could harvest an occasional goat. By the early 1970's urban sprawl was approaching the property and the squatters were being bought out or forced to leave. With the rapid urban expansion of the late '70's, the property suddenly became a wooded island in an upper middle class neighborhood. After MCC selected its nearby location in 1983, the property was sold -- by the square foot! The land is still barren and practically devoid of topsoil. The principal vegetation is cactus, cedar, Texas persimmon, and stunted live oaks. It makes no sense to the midwestern cornbelt immigrant who judges land by the depth and blackness of soil, but to the Central Texan looking for a homesite, the Hill Country is definitely the prestige address.

Cities located along the Escarpment are faced with the choice between encouraging urban development into the hills to the west or onto the prairie to the east. Ecological considerations, conservation of wildlife habitat, and protection of the Edwards Aquifer argue against development in the hills. On the other hand, preservation of prime farmland is a strong argument against urban sprawl further into the coastal plain.

Attempts by both San Antonio and Austin to discourage urban sprawl into the hills by withholding water services have met with limited success. In the Austin area, for example, developers have found that the same services can be purchased from the regional river authority. The controversy may become academic if the proposed scenic parkway linking San Antonio and Austin via the Hill Country becomes a reality. The new parkway is being planned to relieve traffic congestion on Interstate Highway-35, but it is also expected to open a vast new area of prime Hill Country to suburban residential development.

Rapid population growth has put a strain on city infrastructures and the ability to deliver expected services. Traffic congestion has become a problem. Austin residents can expect water rationing every year by mid summer, not because of a water shortage, but because water treatment capacity has lagged behind population growth. Long-time residents perceive a threat to their quality of life.

Despite the frequently-heard contention in San Antonio that the costs of unchecked growth fall unfairly on long-term residents, city government under Mayor Cisneros has continued to encourage growth. The general optimisim among the business community is evident in the booming tourist economy and large-scale downtown construction projects. The most serious opposition to pro-development city government took shape in the summer of 1986 when a San Antonio citzens' group collected the required number of signatures to put the issue of deficit spending and tax increases on the ballot. With overwhelming support from the business and development communities on the one hand, and the large Mexican American population on the other, Mayor Cisneros was never seriously threatened. The measure was defeated by a fifty percent margin. San Antonio is known in the construction and development communities as a good place to do business.

Austin has moved in quite a different direction. After a number of years of business-oriented city government, a new city council and mayor were elected in 1984 with promises to control and direct growth and to protect the quality of life which old-time residents have seen as fast disappearing. "Don't Houstonize Austin," was a frequent admonition of the new regime. Ordinances to limit building height and density, to preserve views, and to maintain water quality have been implemented. A Hill Country Road Ordinance sets limits on building height and density along scenic roadways west of Austin.

Growth-control measures inevitably cause economic hardships in some areas. The Hill Country Road Ordinance, for example, has had considerable economic impact on the investors who purchased the land at inflated prices based on highest possible building density and height. The banks that lent money for purchase of the land are also hurt, as are the architects, contractors and others affected by loss of jobs. The developers accuse city government of being inconsistent and unprogressive, while city government consoles the developers on their poor business decisions. Despite efforts at compromise and talk of working toward common goals, the lines between proponents of rapid growth and the advocates of slower, more controlled growth, seem to be more clearly drawn in Austin than in San Antonio.

By the mid 1980's, however, it was becoming difficult to blame all economic problems on Austin's "no growth" city government. Texas was beginning to feel the economic downturn experienced in other states in the '70's.

Economic Downturn (Bust)

Texas went from a budget surplus of 2.5 billion dollars in 1982 to a projected deficit of about 3 billion in fiscal 1987; from one of the lowest unemployment rates in the nation (5.3%) in 1980, to the highest unemployment rate (about 11%) by mid 1986. It is said that for every decrease of one dollar per barrel in the price of crude oil, 25,000 Texans lose their jobs. Every sector of the State's economy is affected.

Although the Austin-San Antonio area has been spared the depth of economic depression experienced in Houston, Midland/Odessa, and other petroleum centers, by the summer of 1986 there was a noticeable economic slowdown throughout the area. A number of major high-tech firms that had only recently opened Austin facilities were announcing sizeable layoffs. Lockheed, which began Austin operations in 1982 and had built its work force to 2650, began layoffs in the spring of 1986. Data General Corporation announced the closing of its Austin facility with the loss of 375 jobs. Tracor, Burroughs, Texas Instruments, Motorola, and others also announced cutbacks.

The turnaround in the economy has been dramatic. In the early 1980's, the Austin-San Antonio area was a Mecca for the unemployed, especially from the economically-depressed Midwest and Northeast. By the summer of 1986, high unemployment was causing a definite out-migration among certain key groups. The job market for new architects, a good indicator for future construction starts, vanished; architects with no job prospects in Austin could take their pick in Boston. A young Austin architect faced with unemployment went to Boston for two days, had five interviews, received five job offers, came back to Austin and packed her trunk. In the late 1970's it cost at least double to drive a U-Haul truck into Texas; the company had to hire drivers to take them out. By mid 1986 the U-Haul Corporation was charging double or triple to drive a rental truck out of state. Time magazine reported that in May, 1986, the U-Haul Company paid $114,000 to pay people to fly to Florida to drive U-Haul trucks back to Texas (Time, July 14, 1986).

Real estate has suffered along with the rest of the economy. The land rush is over. Homes in Austin that had increased in price an average of 10%-20% annually for several years, suddenly leveled off or began losing value. Tax notices mailed to Austin residents in June 1986, based on seven-month-old appraisals, caused such an outrage that the city agreed to a special reappraisal the next year, one year ahead of schedule. In three wealthy subdivisions to the west of Austin, out of 307 homes in the $400,000+ range which had been on the market in the first half of 1986, only nine had sold by June (American-Statesman, July 3, 1986).

Many speculators who purchased land at the height of the boom have suffered extreme losses. An Austin newspaper announced on June 17 that 41 Austin area properties with loans of one million dollars or more had been posted for possible foreclosure. Among the properties was one owned by the Barnes-Connally Company (former Texas Lieutenant Governor Ben Barnes and former Texas Governor and U.S. Secretary of the Treasury John Connally) which had a loan against it for ten million dollars. It was sold for a fraction of that amount. Barnes-Connally is only one of many companies facing foreclosures and enormous losses from ill-timed land speculation.

As of mid-1986 the Austin and San Antonio skylines belied even a hint of a slow-down in the building industry. The crane was still said to be the "city bird" of Austin. More high-rises were under construction than in any time within memory. But these construction projects had been planned several years before. The question uppermost in the minds of developers and city officials alike was, "who will occupy them?" Overbuilding and low occupancy are likely to be long-lasting legacy of the recent growth binge. As of autumn 1986, there are very few new high-rises on the drawing boards.

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PIPELINE OIL SPILLS AND THE EDWARDS AQUIFERS, CENTRAL TEXAS

Peter R. Rose
Telegraph Exploration, Inc.
P. O. Box 2
Telegraph, Texas 76883

ABSTRACT

Shallow-marine shelf carbonates of the Lower Cretaceous Edwards Group form two important aquifers in central Texas. Both are fractured, cavernous, and highly transmissive. On the Edwards Plateau, the Edwards Group forms a simple, widespread, unconfined aquifer that is the water source for most streams, upland ranches, and many towns. In the Balcones fault zone, the Edwards forms an unconfined aquifer which is recharged by area streams where they cross the Edwards outcrop, and an adjacent confined aquifer farther downdip where the Edwards is overlain by impervious younger formations. The fault-zone aquifer is the main municipal water supply for San Antonio and many other smaller towns, and also provides much of the agricultural and recreational water for the region.

The Edwards is exceptionally vulnerable to pollution from pipeline oil spills, because its high permeability allows spilled crude oil to sink into the bedrock before cleanup crews have time to recover it. Thereafter, moving ground water and irregular pore distribution make recovery operations ineffective. It is estimated that oil spills larger than 999 barrels have the potential for reaching and contaminating the Edwards aquifers. On the average, 40 to 50 percent of spilled oil is recovered in cleanup operations.

The region is crossed by nearly 4,000 miles of pipelines, including small-bore gathering systems, product pipelines, and large-bore trunk pipelines (which pose the greatest hazard because they tend to incur larger spills). In the counties of the Edwards Plateau, Hill Country, and Balcones fault zone, 33 oil spills larger than 999 barrels have been reported since 1971. The largest was 25,200 barrels. Most of the 33 spills were from 10 trunk pipelines, having 10- to 24-inch diameters.

Two proposed large-bore (30 and 42-inch diameter), high-pressure pipelines pose new danger of aquifer pollution. Although the average spill from 30-inch pipelines is about 6,000 barrels, reasonable spill scenarios suggest that spills may commonly be much larger, and conventional mechanical safeguards proposed for such "mega-pipelines" may be inadequate to counter the higher pressures and volumes.

Suggested measures to help protect Edwards aquifers from future oil-spill pollution include:

1. Selective retrofitting of older existing pipelines.

2. Closer spacing of block-valves.

3. Electronically-linked hydrocarbon sensors.

4. Centralized shutdown systems.

5. Establishment of continuously staffed "spill-response stations," strategically located near especially vulnerable areas along the pipeline route.

6. Approval of proposed pipeline routes by the Texas Water Commission, prior to construction.

Additional crude oil pipeline construction over the Edwards aquifers seems imprudent, and an alternative northern route appears much more sound from an environmental viewpoint.

INTRODUCTION

Most of the drinking, agricultural, and recreational water supplies of central Texas come ultimately from highly porous limestone and dolomite aquifers in the Lower Cretaceous Edwards Group. Public awareness of the vulnerability of these aquifers to contamination has been growing in the region for more than 20 years. It reached new heights in late 1985 and early 1986 as a result of the proposal by the All-American Pipeline Company to build a large-bore, high-pressure, heated crude oil pipeline across about 300 miles of combined Edwards outcrop and watershed of streams recharging Edwards aquifers. In trying to make an objective assessment of potential risks posed by the All-American pipeline, it has also been necessary to analyze hazards represented by existing crude oil trunk and products pipelines in the region.

This paper has three purposes:

1. To assess the risk of large oil spills that have the potential to pollute Edwards aquifers.

2. To examine the effects and consequences of aquifer contamination by petroleum liquids from a geological perspective.

3. To recommend measures for reducing potential for pollution of Edwards ground water by oil pipelines.

REGIONAL SETTING AND DEPOSITIONAL HISTORY OF EDWARDS GROUP

A thick succession of resistant, flat-lying, porous, Lower Cretaceous limestone and dolomite, known traditionally as "Edwards," covers much of west-central Texas and composes one of the dominant physiographic elements of the State, the Edwards Plateau (Rose, 1972). Along the northwestern edge of the Gulf Coastal Plain, in the Balcones fault zone, the Edwards is also exposed in fault blocks, where it has been severely altered by ground water. South and east of the Balcones fault zone, the Edwards dips

in Abbott, Patrick L. and Woodruff, C.M., Jr., eds., 1986, **The Balcones Escarpment, Central Texas**: Geological Society of America, p. 163-183

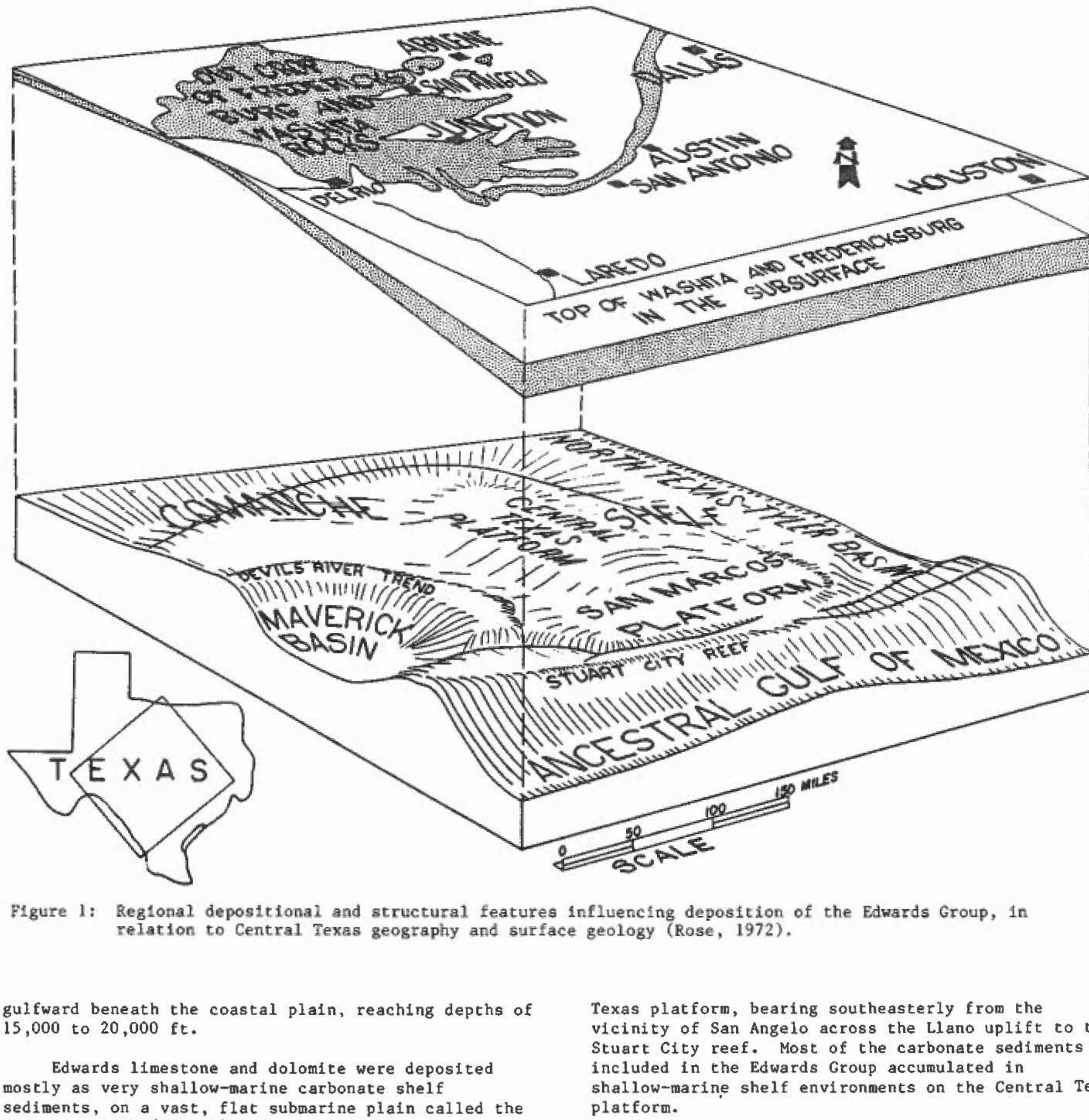


Figure 1: Regional depositional and structural features influencing deposition of the Edwards Group, in relation to Central Texas geography and surface geology (Rose, 1972).

gulfward beneath the coastal plain, reaching depths of 15,000 to 20,000 ft.

Edwards limestone and dolomite were deposited mostly as very shallow-marine carbonate shelf sediments, on a vast, flat submarine plain called the Comanche shelf (Fig. 1). Deeper water lay to the southeast in the ancestral Gulf of Mexico basin. A long, narrow belt of skeletal carbonate sediments, the Stuart City reef (Winter, 1962), marked the gulfward edge of the Comanche shelf. Seaward of the Stuart City reef, water depth apparently increased abruptly, so that open-marine carbonate sediment accumulated in water hundreds of feet deep (Van Siclen, 1958; Winter, 1962). On the Comanche shelf, however, water was generally quite shallow, although there were broad depressions and swells in the interior of the shelf that exerted great influence on thickness and lithology of the Edwards and its counterpart formations. The two dominant depressions were the Maverick basin (Winter, 1962) on the southwest and the north Texas/Tyler basin (Fisher and Rodda, 1967) on the north and northeast. Separating these two depressions was a broad, elongate swell, the Central Texas platform, bearing southeasterly from the vicinity of San Angelo across the Llano uplift to the Stuart City reef. Most of the carbonate sediments now included in the Edwards Group accumulated in shallow-marine shelf environments on the Central Texas platform.

Figure 2 (base map) is a generalized map showing the distribution of major geologic units that crop out in central Texas. Figure 3 shows regional thickness patterns of the Edwards Group and its counterpart formations. This map especially illustrates the wedge form of the Edwards, which thickens in a southwesterly direction from about 100 ft near Waco to about 500 ft throughout most of the Edwards Plateau and Balcones fault zone, to more than 1,000 ft in the Maverick basin where Edwards equivalents lose much of their shallow-shelf character.

Following Edwards deposition, the Central Texas platform was submerged and buried by Upper Cretaceous shales and chalks. Gulfward subsidence had already begun, so depth of burial was much greater to the southeast--up to perhaps 5,000 ft. To the northwest,

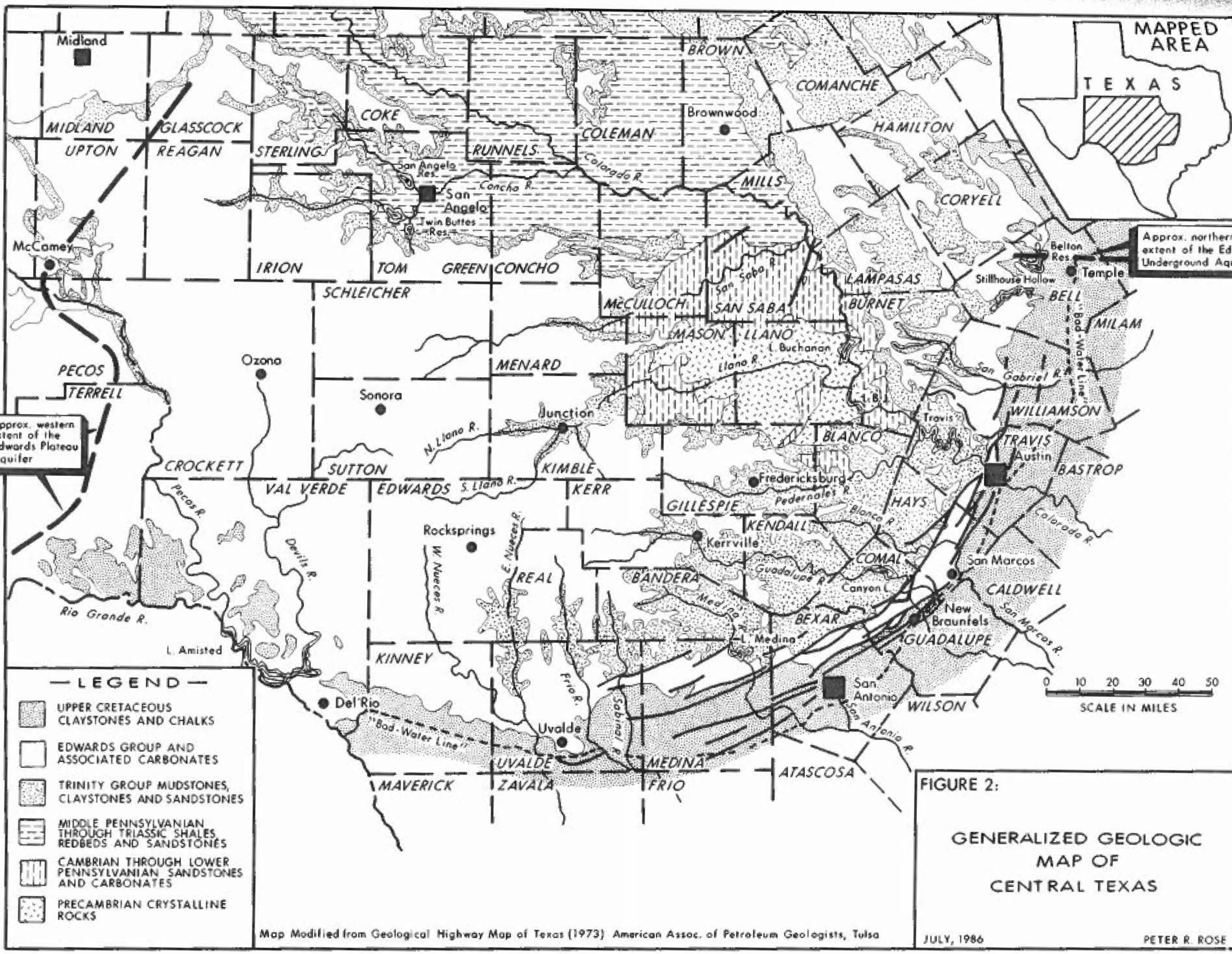


FIGURE 2: GENERALIZED GEOLOGIC MAP OF CENTRAL TEXAS

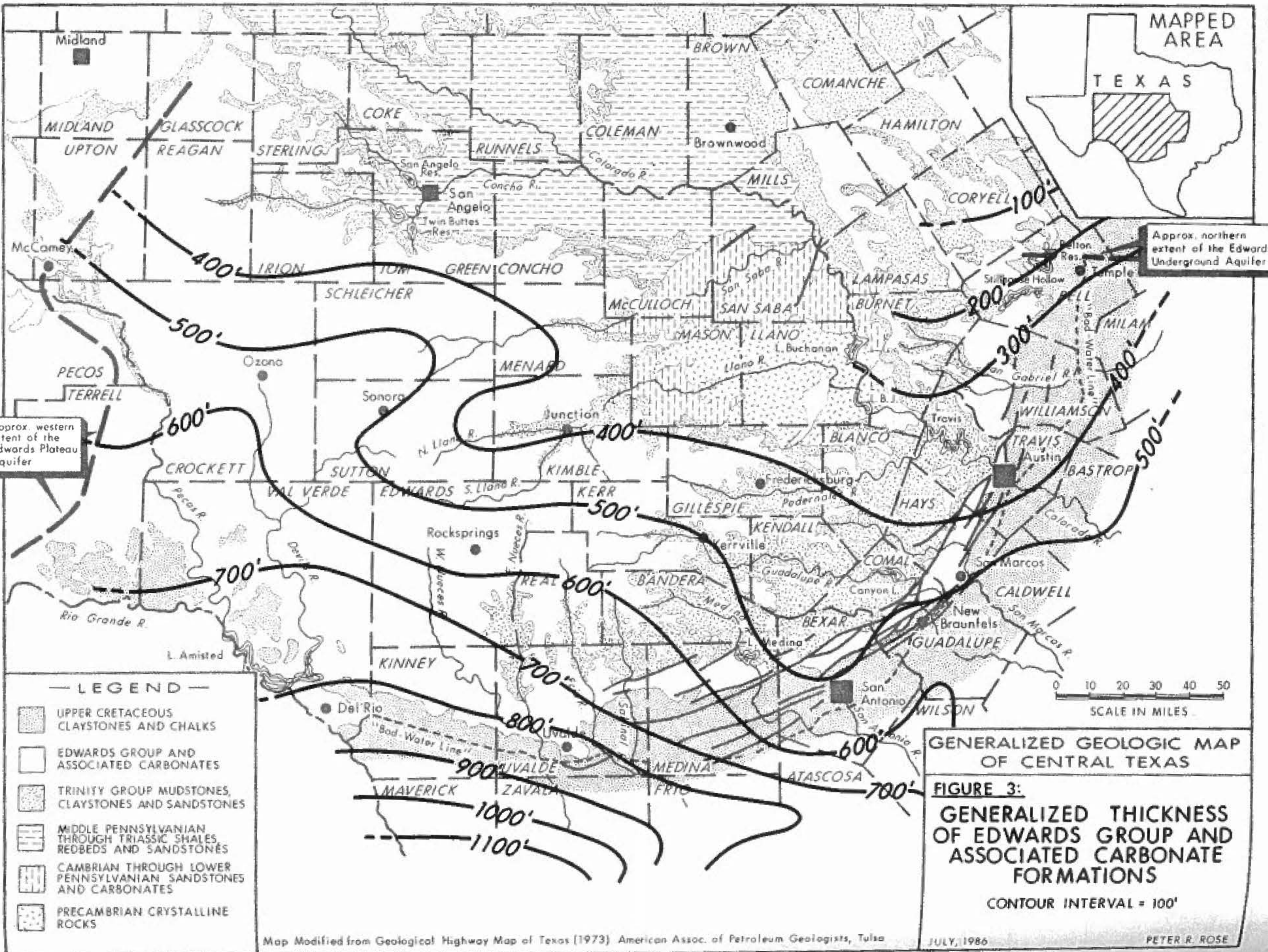


FIGURE 3: GENERALIZED THICKNESS OF EDWARDS GROUP AND ASSOCIATED CARBONATE FORMATIONS

on what is now the Edwards Plateau, and over the perennially-positive Llano uplift, structural contours on the base of the Edwards reflect a broad, domal uplift (Fig. 4).

Edwards carbonates on the Edwards Plateau may never have been buried more than perhaps 1,000-2,000 ft. Gradual emergence began during early Eocene, and by the time of Balcones faulting (Miocene), it is probable that the top of the resistant Edwards carbonate mass in the Edwards Plateau region was subaerially exposed, and karstification processes were acting on the carbonate terrane. Especially in the Balcones fault zone, such subaerial solutional processes were already enhancing early Edwards porosity, precursors to the fault-bound sluiceway that would develop later into the Edwards underground aquifer of the Balcones fault zone trend (Abbott, 1975; Woodruff and Abbott, 1979). Post-Miocene headward erosion formed the "Hill Country" region, northwest of the Balcones fault zone and southeast of the Edwards Plateau proper, by removal of Edwards divides, leaving a highly dissected terrain of Glen Rose hills and valleys. During the past 10 million years, continued uplift and erosion to the northwest, and subsidence beneath the Gulf Coastal Plain to the southeast, have produced the present geological configuration of the Edwards Plateau, "Hill Country," Balcones fault zone, and Gulf Coastal Plain (Fig. 5).

SUMMARY OF THE GEOLOGY AND HYDROLOGY OF THE EDWARDS AQUIFERS

Edwards Plateau Aquifer

The Edwards Plateau aquifer is a simple, widespread, flat-lying, unconfined aquifer in the lower part of the Edwards Group. The aquifer is present--in fact, is the sole or dominant aquifer--in all, or large parts, of 19 Texas counties (Figs. 2 and 5; Glasscock, Sterling, Coke, Pecos, and Terrell Counties are excluded based on lithologic and hydrologic criteria). The lower part of the Edwards succession is an aquifer because claystones, mudstones, and sandstones of the underlying Glen Rose, Hensell, and Antlers formations of the Trinity Group are, for the most part, aquitards, or at least much less permeable than the honeycombed and cavernous limestones and dolomites of the lower Edwards Group. As a result of this differential permeability, rain water and run-off water percolate downward through the cavernous carbonate sequence and accumulate above the base of the Edwards. Thickness of the saturated zone varies, of course, but water columns in excess of 200 ft thick are common. This ground water then moves laterally, emerging as prolific springs which form the headwaters of streams draining radially from the Edwards Plateau: the Concho, San Saba, North and South Llano, Pedernales, Blanco, Guadalupe, Medina, Sabinal, Frio, East and West Nueces, and Devils rivers (Figs. 2 and 5).

Edwards permeability is very high because of karstic porosity development, such as sinkholes, caverns, horizontal fissures, and honeycombed zones. In addition, the Edwards Plateau is crisscrossed by a network of tectonic fractures and joints (Wermund, et al., 1978) which provide effective avenues for both vertical and lateral migration of ground water through the carbonate mass. As a result, water moves downward to the top of the water table very rapidly--within hours or, at most, several days. Many area residents can describe small caves in cliff walls from which issue strong, but temporary, water-flows a day or so after summer cloudbursts occur miles away on top of the plateau.

Even though sinkholes and solution-enlarged fractures are present throughout the Edwards Plateau area, matrix porosity and permeability increase to the southeast. There are multiple causes for this lateral variation in aquifer quality:

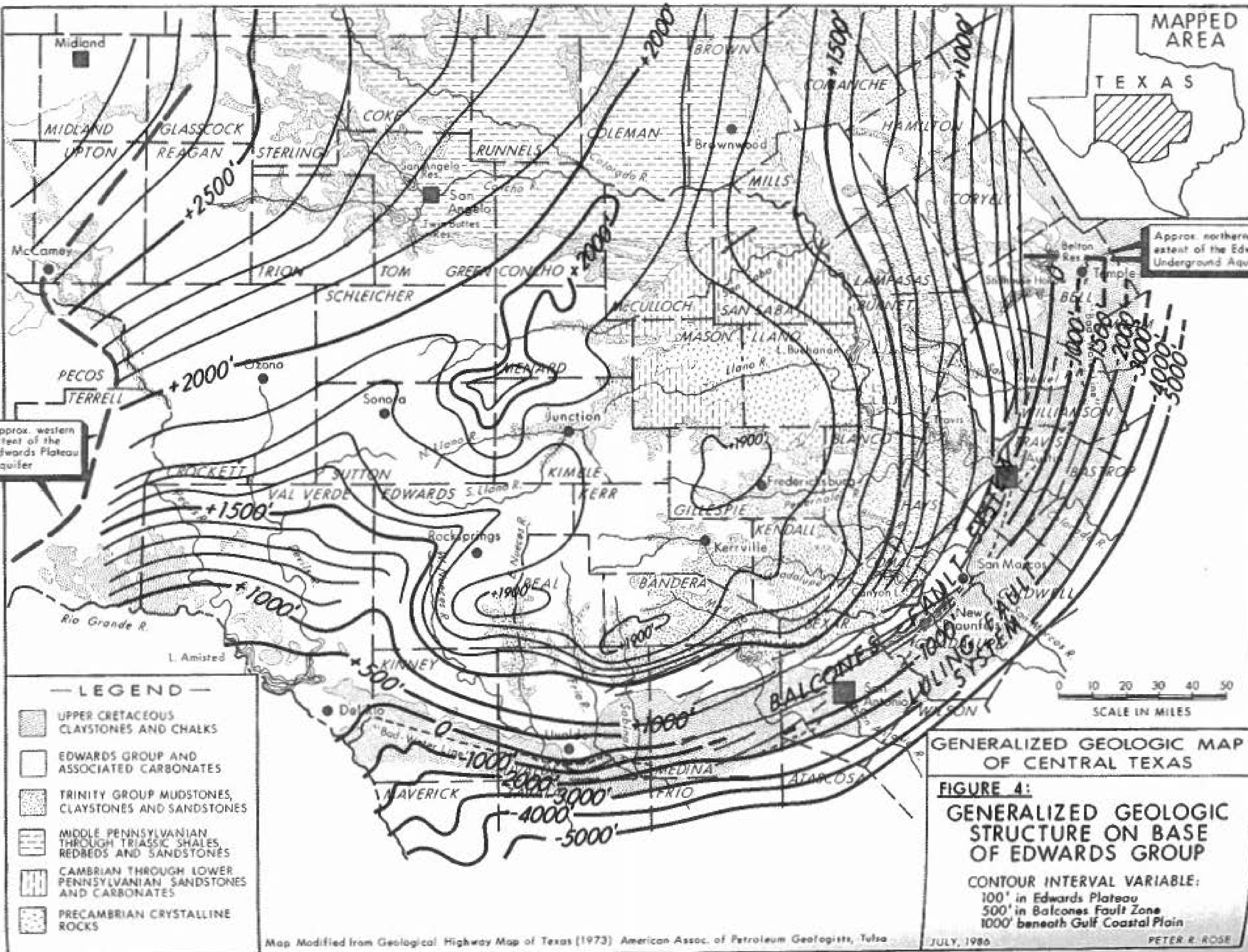
1. Evaporite solution-collapse breccias are concentrated over the interior of the Central Texas platform, where evaporitic-restricted environmental conditions were maximized. Such collapse-breccia zones are particularly prone to porosity enhancement and, thus, to cavernous permeability development.

2. For similar environmental reasons, dolomite is much more abundant in the interior of the Central Texas platform, and dolomite tends to be more porous and permeable than limestone, other factors being equal.

3. Annual rainfall increases in an easterly direction across the Edwards Plateau. There is ample evidence that ground water has acted as a "positive feedback process" that has steadily enhanced porosity and permeability in the Edwards aquifer (Abbott, 1975; Woodruff and Abbott, 1979; Maclay and Small, 1984). In other words, the more water available to move in and through the aquifer, the more enhancement of secondary porosity will occur.

Overall, however, porosity and permeability increase downward in the Edwards section, again reflecting the long-term influence of ground-water saturation, movement, and enlargement of pores and vugs. Honeycomb porosity zones are especially common in the lower part of the Edwards aquifer. Such vuggy networks seem to develop preferentially in burrowed limestones and dolomites, as well as in rudist limestones in which individual rudistids are preferentially dissolved, leaving a vuggy limestone matrix. About 200 ft above the base of the Edwards, a widespread evaporate solution-collapse horizon, the Kirschberg evaporite, also forms a horizontal zone of high transmissibility.

In the northern part of the map area, the Edwards is underlain by siltstones and sandstones of the Antlers and Hensell sandstones of the Trinity Group, with which the Edwards may be in hydrologic continuity, even though such sandstone aquifers generally yield much less prolific flows. However, impervious claystones and mudstones of the Glen Rose Formation intervene wedge-like in the Trinity, going southward and eastward, between the Hensell (or Travis Peak) Sandstone and the overlying Edwards. As a result, these sandstones are no longer in continuity with the Edwards and, in fact, these sandstone aquifers become artesian, because the overlying tight Glen Rose serves as a confining aquitard. Also, aquifer-quality sandstones in the Hensell/Antlers/Travis Peak are commonly erratic in their distribution. For these reasons, the classification by the Texas Department of Water Resources (Walker, 1979), which treats the Edwards and Trinity as one aquifer in the Edwards Plateau region, is clearly a misleading and inappropriate simplification.


MAPPED AREA
TEXAS
Approx. northern extent of the Edwards Underground Aquifer
Approx. western extent of the Edwards Plateau Aquifer
— LEGEND —
UPPER CRETACEOUS CLAYSTONES AND CHALKS
EDWARDS GROUP AND ASSOCIATED CARBONATES
TRINITY GROUP MUDSTONES, CLAYSTONES AND SANDSTONES
MIDDLE PENNSYLVANIAN THROUGH TRIASSIC SHALES, REDBEDS AND SANDSTONES
CAMBRIAN THROUGH LOWER PENNSYLVANIAN SANDSTONES AND CARBONATES
PRECAMBRIAN CRYSTALLINE ROCKS
SCALE IN MILES
0 10 20 30 40 50
BALCONES FAULT ZONE
LULING FAULT SYSTEM
+2500'
+2000'
+1500'
+1000'
+500'
0
-1000'
-2000'
-3000'
-4000'
-5000'
+1900'
Midland
McCamey
Ozona
Sonora
Junction
Rocksprings
Kerrville
Fredericksburg
San Angelo
Brownwood
Temple
San Marcos
New Braunfels
Del Rio
Uvalde
San Antonio
L. Amistad
Rio Grande R.
MIDLAND
GLASSCOCK
UPTON
REAGAN
STERLING
COKE
RUNNELS
COLEMAN
BROWN
COMANCHE
HAMILTON
MILLS
CORYELL
TOM GREEN
CONCHO
IRION
SCHLEICHER
MCCULLOCH
SAN SABA
LAMPASAS
BURNET
BELL
MASON
LLANO
MENARD
PECOS
TERRELL
CROCKETT
SUTTON
KIMBLE
WILLIAMSON
TRAVIS
BLANCO
BASTROP
GILLESPIE
HAYS
VAL VERDE
EDWARDS
KERR
KENDALL
COMAL
CALDWELL
REAL
BANDERA
BEXAR
KINNEY
WILSON
MEDINA
FRIO
ATASCOSA
MAVERICK
Map Modified from Geological Highway Map of Texas (1973) American Assoc. of Petroleum Geologists, Tulsa
GENERALIZED GEOLOGIC MAP OF CENTRAL TEXAS
FIGURE 4:
GENERALIZED GEOLOGIC STRUCTURE ON BASE OF EDWARDS GROUP
CONTOUR INTERVAL VARIABLE:
100' in Edwards Plateau
500' in Balcones Fault Zone
1000' beneath Gulf Coastal Plain
JULY, 1986
PETER R. ROSE

GENERALIZED GEOLOGIC MAP OF CENTRAL TEXAS

FIGURE 5:

MAIN GEOLOGIC AND HYDROLOGIC PROVINCES AFFECTING THE EDWARDS AQUIFERS, CENTRAL TEXAS

JULY, 1986 PETER R. ROSE

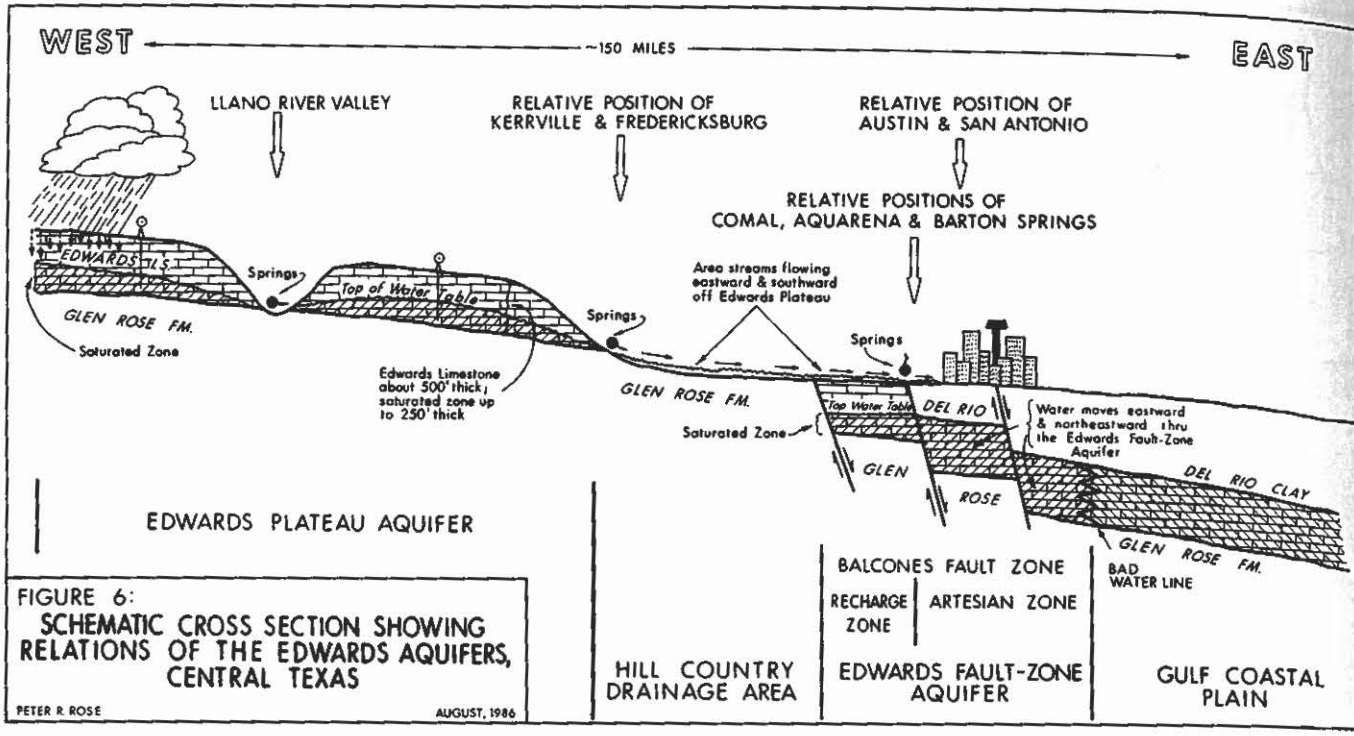


FIGURE 6:
SCHEMATIC CROSS SECTION SHOWING RELATIONS OF THE EDWARDS AQUIFERS, CENTRAL TEXAS

Balcones Fault Zone Aquifer

The basic geohydrology of the Edwards aquifer in the Balcones fault zone is, by now, well understood and has been capably described by many authors, especially Arnow (1959), Abbott (1975), Maclay and Small (1984), and Senger and Kreitler (1984). The following brief review merely summarizes the conclusions of many previous workers. Because of the presence of other carbonate formations and facies, such as the thin Georgetown Limestone which overlies the Edwards, and the Devils River, Salmon Peak, McKnight, and West Nueces formations, which are lateral facies equivalents of the Edwards, hydrogeologists have adopted the useful term "Edwards and Associated Limestones" to refer to the hydrogeologic carbonate aquifer unit in the Balcones fault zone province.

In the Balcones fault zone of central Texas, Edwards and associated limestones are present in a series of linear fault blocks which trend eastward through Kinney, Uvalde, and Medina Counties and thence northeastward through Bexar, Comal, Hays, Travis, and Williamson Counties. Structure contours on the base of the Edwards (Fig. 4) indicate that vertical displacement across the several en echelon faults of the Balcones system totals about 1,000-1,500 ft in the Austin/San Antonio corridor and perhaps half that amount west of San Antonio, in Medina and Uvalde Counties.

Streams draining southward and eastward from their sources in the Edwards Plateau, such as the East and West Nueces, Frio, Sabinal, Medina, Guadalupe, and Blanco rivers cross a belt of Glen Rose outcrop, between the Edwards Plateau to the west and the Balcones fault zone to the east, called here the Hill Country drainage area (Figs. 5 and 6). This belt represents the area in which headward erosion since the Miocene has stripped resistant Edwards carbonates away, leaving the mudstones and carbonates of the underlying Glen Rose Formation at the surface. Farther east, these streams then flow across outcropping Edwards carbonates in downthrown Balcones fault blocks, and much of their water moves downward, recharging the Edwards aquifer of the fault zone. Therefore, where the Edwards crops out in the Balcones fault zone, the aquifer in the lower part is, for the most part, unconfined, analogous to the plateau aquifer.

Slightly farther eastward and southward, however, the Edwards dips underground, covered by relatively impermeable younger formations such as the Del Rio clay and Eagle Ford clays. These argillaceous formations serve as top-seals. Where they are present, the subsurface Edwards forms a confined, or artesian, aquifer. At distances of 1-20 miles downdip from the Edwards outcrops of the Balcones fault zone lies the "bad water line," a remarkable hydrologic boundary within the Edwards, marking the abrupt transition from fresh water (250-450 mg/l total dissolved solids) to sulphurous salt water (more than 1,000 mg/l total dissolved solids). Fresh ground water moves generally eastward across Kinney, Uvalde, and Medina Counties then northeastward across Bexar, Comal and southern Hays Counties within the confined "Edwards underground aquifer," and emerges at San Marcos Springs, the lowest discharge point along the fault zone. About halfway between San Marcos and Austin, in northern Hays County, may be located a vague "ground-water divide," defined by a potentiometric high (Senger and Kreitler, 1984). Water appears to flow southwestward from that divide to San Marcos Springs and northward to Barton Springs in Austin (Slade, et al., 1985). Apparently, the narrow belt of the Edwards underground aquifer has long served as a natural subsurface sluiceway, possibly even since the Miocene (Abbott, 1975; Woodruff and Abbott, 1979). Because of this long history and the "positive feedback" effects of ground-water solution on aquifer transmissibility, reservoir rocks within the Edwards underground aquifer are much more porous and permeable, with a markedly more cavernous character, than Edwards rocks downdip of the "bad water line."

Prolific permanent springs are present along the fault-bounded south and east margins of the Edwards outcrop. Discharge from Comal Springs, near New Braunfels, is mostly artesian, derived from the confined Edwards underground aquifer. At San Marcos Springs, as well as at Barton Springs in Austin, discharge is from both the unconfined Edwards of the recharge zone, as well as from the artesian Edwards of the Edwards underground aquifer.

As pointed out by Abbott (1975), the upper part of the Edwards Group in the Balcones fault zone appears to be more cavernous and permeable than the lower part, possibly because of the presence in the middle of the Edwards succession of a slightly argillaceous, tight limestone layer, the Regional Dense Member, and/or because of Cenozoic enhancement of porosity created by mid-Cretaceous subaerial exposure and karstification in the upper part of the Edwards (Rose, 1972).

IMPORTANCE OF EDWARDS AQUIFERS IN CENTRAL TEXAS

There are two Edwards aquifers. They are the most sensitive aquifers in Texas, and they are crucial to the water supplies and character of the central Texas region.

In the Edwards Plateau, upland ranches throughout this sparsely populated region derive nearly all of their agricultural water from the unconfined Edwards aquifer, commonly via windmill-powered water wells. Towns such as Ozona, Sonora, and Rocksprings also get their municipal water from Edwards water wells; streams fed by Edwards springs provide water supplies to towns such as Junction and Kerrville. Limited irrigation, primarily in cultivated river valleys, depends on water supplied by such streams. The Llano, Pedernales, Guadalupe, Medina, and Devils rivers, which issue from spring-fed streams in the Edwards Plateau and drain eastward and southward across the Hill Country drainage area (Fig. 5), are major contributors to area lakes used for storage, irrigation, power, and recreation, such as LBJ, Travis, Austin, Canyon, Medina, and Amisted lakes. Also, such streams are the primary source of fresh water for recharge of the second Edwards aquifer in the Balcones fault zone.

The Edwards underground aquifer provides most of the municipal water supply for the City of San Antonio. In addition, smaller towns such as Uvalde, Hondo, New Braunfels, and San Marcos derive their water from Edwards springs or water wells. Smaller semi-rural residential developments, ranches, and considerable irrigated farming all depend on water from the Edwards underground aquifer. A number of spectacular springs, such as Barton Springs in Austin, represent cherished recreational and scenic locales to the central Texas community.

The importance and vulnerability to pollution of the Edwards aquifer in the Balcones fault zone led to the creation of the Edwards Underground Water District by the Texas Legislature in 1959. Proceedings are now underway to create a second underground district, in the Austin sector of the Balcones fault zone, north of the previously discussed ground-water divide in Hays County. Special zoning and construction restrictions are in effect for most counties in the fault zone area, reflecting the high public awareness of the fragility of the hydrogeologic system.

PIPELINE OIL SPILLS

Like most events that are caused by a combination of independent variables, such as rainfall or mineral deposits, pipeline oil spills appear to fit what is called a "lognormal" distribution (Fox, et al., 1976). The basic attribute of any lognormal distribution is that there will be, in the total population, a very large number of small occurrences, a moderate number of intermediate occurrences, and only a few very large occurrences. A perfectly lognormal distribution will plot as a straight line on a special kind of graph paper, called "lognormal probability paper."

In Texas, all oil spills of five barrels or more are required to be reported by pipeline operators to the Texas Railroad Commission; some operators also report spills of smaller volume. Volume, location, date, recovery, and cause of spills must be reported. Pipelines are separated into three classes: crude oil trunk lines, gathering lines, and product lines. Total line-miles in each class vary somewhat from year to year, but the average total for the State from 1971 through 1985 was 75,266 miles: crude oil trunk lines were 25,738 miles; gathering lines were 26,968 miles; and product lines were 22,560 miles. Computerized spill reports do not indicate the class of pipeline from which the spill occurred.

Texas Spill Statistics

From 1971 through 1985, 15,260 pipeline oil spills were reported to the Texas Railroad Commission (Table 1). Curve A, in Figure 7, shows the probability distribution of these spills: 40 percent were larger than 49 barrels in volume, about 28 percent were more than 99 barrels, and nearly 3 percent were 1,000 barrels or more. For the 15-year period, the spill-rate (all spills) was one spill per 78.4 line-miles of pipeline per year (Table 1 and Fig. 8, Curve A). For spills of 50 barrels or more, the spill-rate was one spill per 189.1 line-miles per year. Spills of 1000 barrels or more occurred at the rate of one per 2,752.2 line-miles per year. Mean spill size was about 215 barrels and median spill size was about 36 barrels, again reflecting the lognormality of spill distributions. The largest spill reported during the 15-year period was 30,185 barrels, from a Chevron pipeline in Hudspeth County.

Pipeline spills in Texas are occurring with decreasing frequency; for example, 1,403 spills were reported in 1971 versus 751 in 1984. Although all classes of spills decreased, the greatest decrease (nearly 50 percent reduction) occurred among spills smaller than 50 barrels, whereas spills larger than 500 barrels showed a reduction of about 35-40 percent. This would appear to mean that pipeline operators are preventing smaller spills more successfully than they are preventing larger spills.

The most common reported causes of Texas pipeline oil spills are: corrosion, equipment failure, human error, and "other causes." In the latter two categories, most incidents relate to heavy equipment cutting the pipeline. Although the Texas Railroad Commission data indicate corrosion to be the single largest cause of pipeline oil spills, the U. S. Department of Transportation, Materials Transportation Bureau (1985) indicates that "outside force damage" is the leading cause of pipeline factors, followed by external corrosion and "leaks in system components other than pipe." It appears that considerable latitude exists in accounting for causes of spills. For example, a large oil spill in 1979 by Exxon in

Table 1. Statewide Data, Texas--All Pipelines

A. All Texas Pipeline Oil Spills--1971-1985:

Total spills .... 15,260 = 100.0% (average per year: 1,017)

Spills greater than 49 barrels	6,211 =	40.7%	(average per year: 414)
Spills greater than 99 barrels	4,239 =	27.8%	(average per year: 282)
Spills greater than 199 barrels	2,498 =	16.4%	(average per year: 167)
Spills greater than 499 barrels	973 =	6.4%	(average per year: 65)
Spills greater than 999 barrels	434 =	2.8%	(average per year: 29)

Mean spill = 215.4 barrels
Median spill = 36.8 barrels

B. Texas Pipeline System--1971-1985:

Crude oil trunk lines	(average 1971-1985) =	25,738 miles
Gathering lines	(average 1971-1985) =	26,968 miles
Product lines	(average 1971-1985) =	22,560 miles
Total	(average 1971-1985) =	75,266 miles

C. Average Annual Spill-rates--1971-1985:

All spills: one spill per 78.4 line-miles per year.

Spills greater than 49 barrels: one spill per 189.1 line-miles per year
Spills greater than 99 barrels: one spill per 276.4 line-miles per year
Spills greater than 199 barrels: one spill per 469.8 line-miles per year
Spills greater than 499 barrels: one spill per 1,217.6 line-miles per year
Spills greater than 999 barrels: one spill per 2,752.2 line-miles per year

FIGURE 7: CUMULATIVE PERCENT DISTRIBUTION OF OIL PIPELINE SPILLS (1971 - 1985)

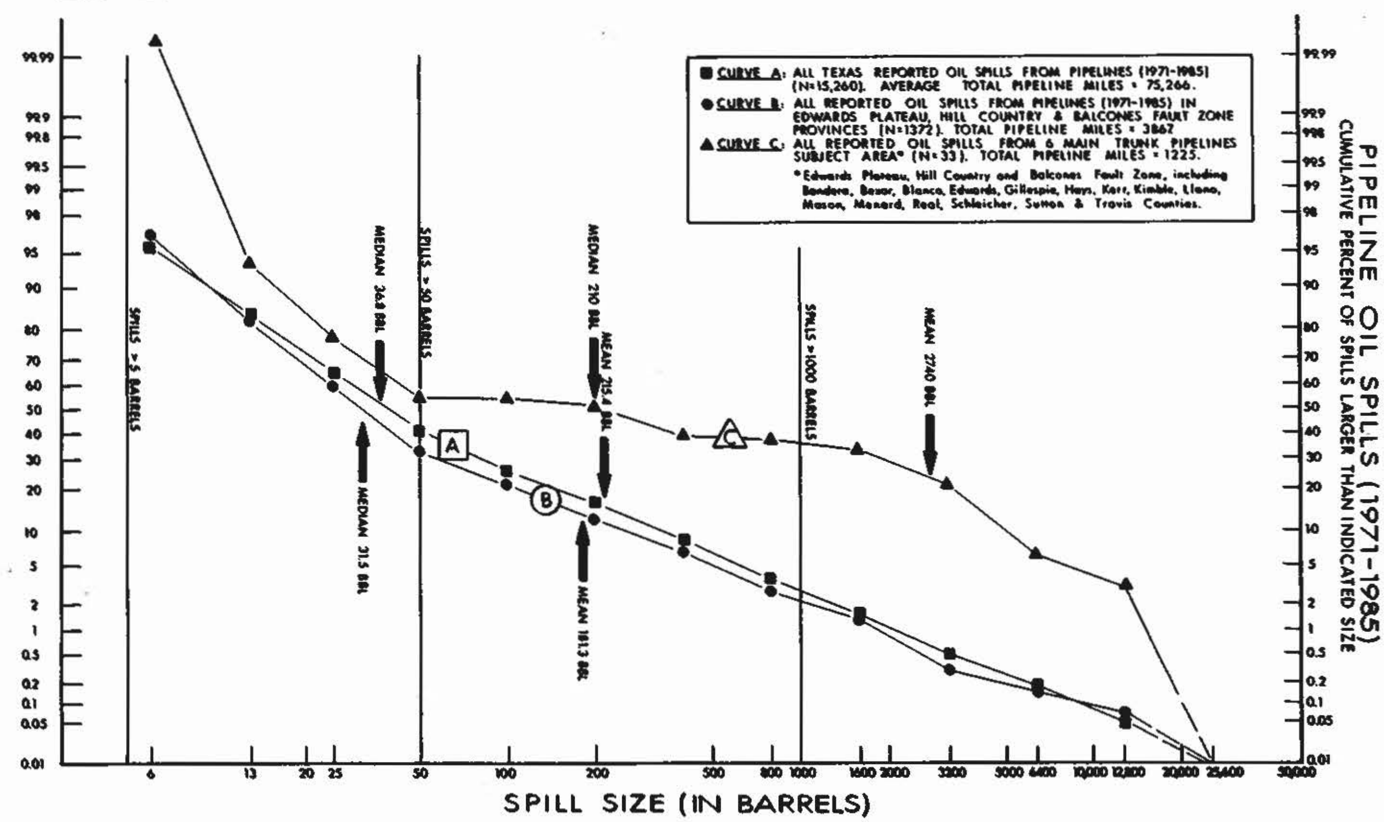
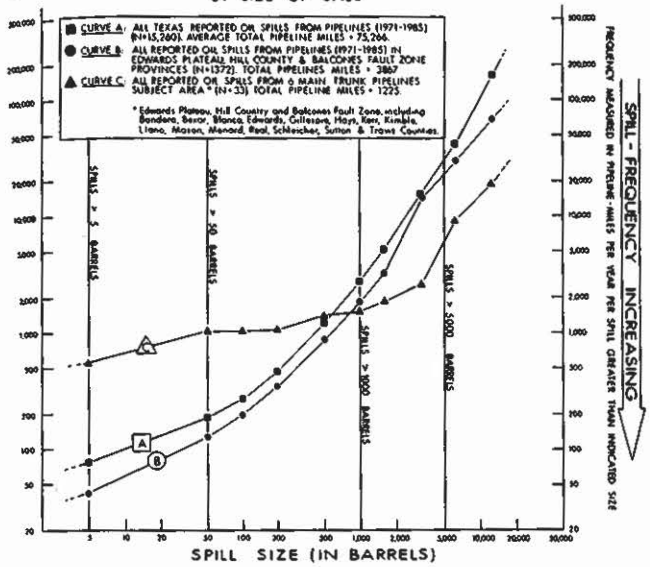


FIGURE 8: FREQUENCY OF PIPELINE OIL SPILLS (1971-1985) BY SIZE OF SPILL



Kimble County (25,224 barrels), is shown on Texas Railroad Commission computer reports as caused by corrosion--despite other evidence that the spill was caused by a longitudinal split in the 18-inch pipe.

Typical Sequence of Events in an Oil Spill Incident

Most pipeline oil spills are detected by landowners or other passers-by, by heavy equipment operators whose activity caused the pipeline rupture, by company personnel patrolling the pipeline, or by company personnel monitoring pumping stations or pipeline terminals. Some newer pipelines may be fitted with special electronic hydrocarbon-detection sensors to identify leaks. Many experienced pipeliners indicate that spills of smaller than about 0.1 percent of daily shipping volume are difficult to detect volumetrically. Most small spills of less than, say, 50 barrels, and most leaks on older pipelines are detected by manual means. Many small, chronic leaks (so-called "ghost leaks") may be very difficult to locate, once detected.

Large leaks may cause abrupt drops in pressure, which can be detected in pumping stations or terminals. Larger, more modern pipeline systems may have monitoring systems which can indicate the sector of the break, allowing rapid shutdown of the pipeline, closing of block-valves, and preferential evacuation of downstream segments to reduce outflow. Such monitoring systems may also alert cleanup and repair crews promptly and direct them to the general location of the accident.

In the event of a large leak, the entire pipeline system must be shutdown, which ordinarily requires a human decision. Pipeline transmission cannot be stopped instantly-- block-valves are closed gradually over a period of perhaps 5-15 minutes. In addition to the oil which spilled out before shutoff of transmission, a certain amount of oil between the break and the nearest upstream block-valve also may leak out of the pipeline. Spacing of such valves varies, but for the newest proposed pipeline in Texas, average spacing between block-valves was about 18 miles. Accordingly, the time between rupture and complete shutdown, the distance between the break and nearest upstream block-valve, the size of the rupture, the terrain-slope, the diameter of the pipe, the current shipping pressure, and the API gravity of the product all affect the total volume spilled.

Once a large oil spill is detected and located, operators generally respond as quickly as possible by shutting down transmission and dispatching repair and cleanup crews to the scene. Some commonly employed equipment and procedures include the following:

1. Bulldozers to build temporary earthen retaining berms.

2. Back-hoes to make ditches and gathering systems.

3. Deployment of plastic-lined catchment systems.

4. Vacuum trucks to collect spilled oil from ditches, catchment basins, and rivers or lakes.

5. Cultivators to till and retill oil-saturated ground so as to let the spilled oil evaporate, volatize, and be consumed by soil bacteria.

6. Booms and other blocking devices to collect crude oil that has spilled into streams or lakes.

Analysis of reported spills and recoveries suggests that, on average, operators recover about 40-50 percent of oil spilled in pipeline accidents involving 1,000 barrels or more, about 60 percent in spills of 100-1,000 barrels, and about 40 percent of smaller spills. This does not take into account problems in correctly measuring and reporting true sizes of spills, nor does it account for the 10-15 percent "typical" rate of simple evaporation, which renders suspect many reported recoveries that approach 100 percent of the amount claimed to have been spilled. Generally, calculated spill-volumes are probably accurate within about 10-15 percent plus or minus the actual volume spilled, and there may be room for improvement in reporting accuracy of pipeline spills and recoveries to the Texas Railroad Commission.

Depending on the location and accessibility of the accident site, it may take several hours or longer for cleanup and repair operations to begin. Many weeks of cleanup work may be required to achieve maximum possible correction. Oil spills may lead to serious fires and other human hazards. More common negative effects include killed trees; crop land or pasture land rendered barren for some years; contaminated lakes and streams; infertility, illness, or mortality of livestock and game; fish and waterfowl mortality; and ground water contaminated by hydrocarbons and heavy metals.

In fairness, however, it should be pointed out that most oil spills, especially smaller ones, do not generally cause permanent environmental destruction. Nature does eventually clear herself up, but years and much damage may ensue in the process.

Construction and Retrofitting Countermeasures

Although pipeline companies are clearly motivated to prevent oil spills, their natural corporate interest is in avoidance of crude oil loss and in the mechanical integrity of the pipeline facility. The issue of environmental damage would appear to be of secondary priority, impacted more by concerns of their corporate public image. For that reason, new pipeline projects may resist the imposition of closer-spaced block- and check-valves; more numerous, continuously maintained, repair/cleanup stations; frequent collection sumps; clay liners; concrete-lined marginal ditches; larger-diameter outer sleeves; and other design measures aimed at minimizing the effects of oil spills once they occur.

A second aspect of limitation of environmental damage during the design/construction phase has to do with pipeline routes. Obviously, there is substantial financial incentive to choose routes offering lowest construction costs, of which distance is probably the most significant. However, some routes offer intrinsic advantages over others vis-a-vis the environmental consequences of pipeline oil spills. In Texas, there is no statutory or regulatory provision applying to location of a proposed pipeline--the pipeline route is entirely in the hands of the pipeline company, which also is endowed with the right of eminent domain. The Texas Railroad Commission grants permits to operate pipelines, not to construct them, and such permits have generally been issued in the past on a pro forma basis. In addition, the Texas Railroad Commission has been assigned the responsibility to safeguard surface and subsurface water supplies from pipeline pollution, even though the Texas Water Commission clearly has the philosophical mandate and technical personnel for such regulation.

Many Texas pipelines are more than 60 years old. Given the cumulative effects of corrosion, we might expect increasing spill frequencies in these older lines. However, Texas spill-statistics would seem to indicate pipeline safety to be improving over time. The question of retrofitting of older pipelines, especially those showing an increased spill-rate, however, is an issue that must eventually be faced. This is especially true in areas of population concentration, environmental sensitivity, and fragile aquifers. Indeed, given the pace of suburban development, expanding population, and the recognition of actual historical spill-rates, the question of retrofitting may be applied even to pipelines that do not have histories of increasing spill-frequencies.

EFFECTS OF OIL SPILLS ON CARBONATE AQUIFERS

Spilled oil seeps into the ground, obeying forces of gravity and capillarity. The amount of oil that seeps downward into the bedrock depends on many variables, including:

1. The amount of oil spilled.
2. The rapidity of the spill.
3. The viscosity of the spilled oil.
4. The temperature of the ground surface.
5. The amount of vegetative and soil cover.
6. The slope of the terrain.
7. The porosity and permeability of the bedrock.
8. The moisture or water saturation of the bedrock.
9. The response time and effectiveness of cleanup crews.

Obviously, bedrock characterized by a network of very small pores, such as a fine-grained sandstone, will not accept or transmit spilled oil as rapidly as a cavernous, honeycombed limestone. Very large or extensive fractures or bedding fissures also promote rapid transmission of surface fluids downward into the bedrock. Pervasive matrix porosity can absorb a great deal of crude oil. Thin soils and sparse vegetative cover may lead to increased absorption into bedrock. Remote or inaccessible terrain may delay the arrival of cleanup crews until much of the spilled crude oil has flowed downward into the bedrock.

For the reasons outlined above, it is very difficult to determine or predict how large an oil spill must be before it will reach and contaminate a carbonate aquifer. Construction of a series of "reasonable models" led the writer to conclude that any oil spill of 1,000 barrels or more represented a reasonable danger of reaching the water table in the Edwards Plateau area.

All of the above factors make carbonate bedrock more susceptible to oil-spill pollution than sandstone. When oil seeps down through unsaturated bedrock and reaches the ground-water table in an unconfined aquifer, it then spreads out on top of the water surface. The rate of spread is highly sensitive to aquifer permeability, but tends to be rapid and extensive. For example, one barrel of standard 10W30 motor oil will form a "rainbow" covering about 200 acres of standing water. By analogy, in a highly cavernous carbonate aquifer having about 15 percent porosity, one barrel of oil could cover more than two square miles of the water table. Of course, capillary pressure acting on fine matrix porosity would be expected to absorb much of this oil and retard lateral spreading. Free oil entering an unconfined aquifer would be expected to spread and travel in the direction of water flow, emerging eventually at springs and showing up wherever wells sampled the top of the water column. One of the more insidious effects of crude oil contamination of an aquifer is the dissolution of some hydrocarbon components, such as benzene and heavy metals, which can be toxic in minor concentrations in fresh water. Moreover, the lighter hydrocarbon fractions tend to be more toxic, and they also tend to spread more readily on water.

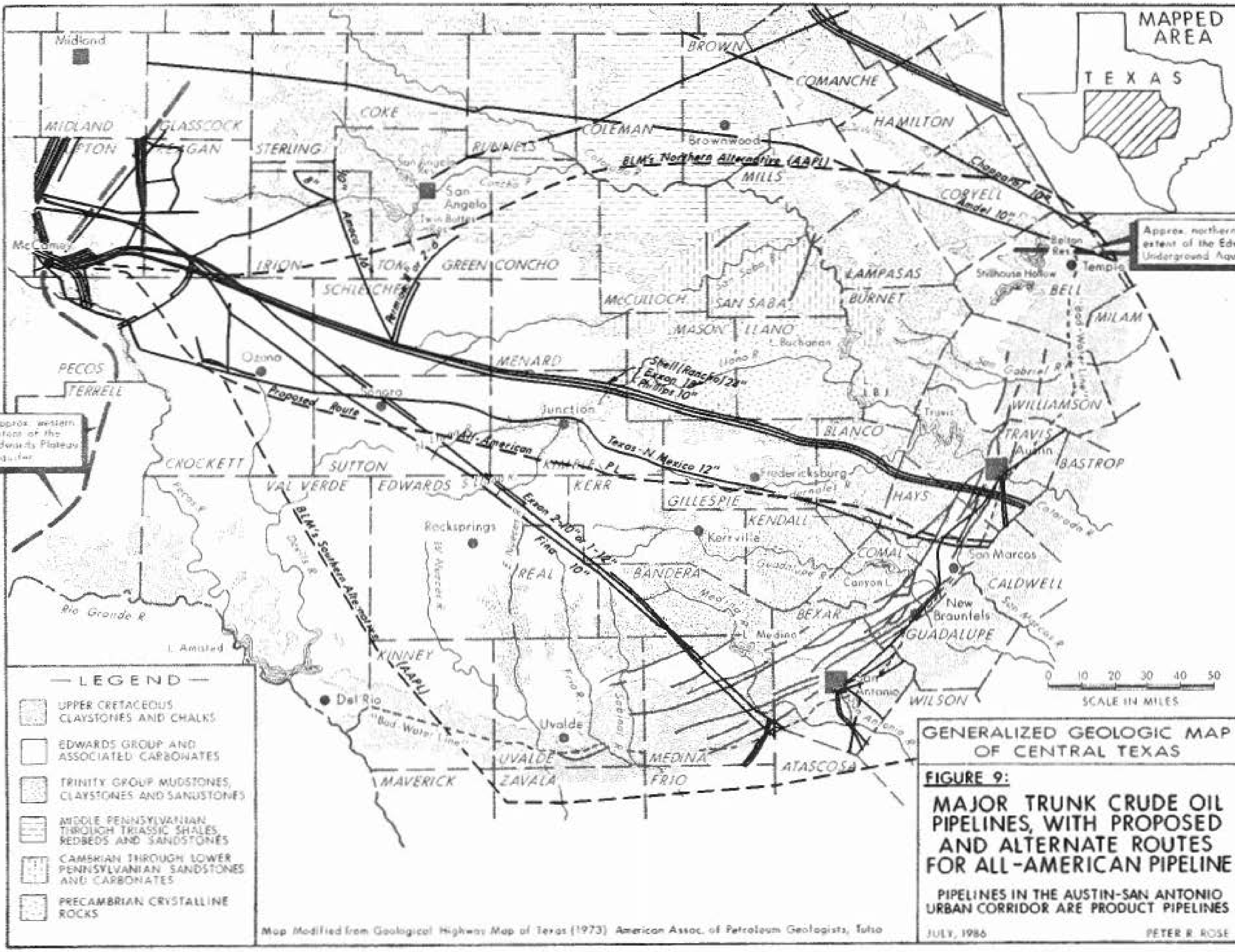
It is much more difficult to introduce spilled oil into a confined aquifer simply because, by definition, such an artesian aquifer sealed from above is "full" and under pressure, so that the buoyant oil droplets cannot enter the water column. However, soluble crude oil components can be introduced into confined aquifers.

Several methods have been suggested to recover spilled oil from aquifers, including closely spaced, intensively pumped relief wells surrounding the spill site, and the introduction of petroleum-consuming bacteria. Carbonate aquifers in which ground water is moving at rates of a few feet per day through irregular, cavernous fissures do not lend themselves to either approach. Natural biodegradation processes tend to act slowly in fresh-water aquifers. Most knowledgeable hydrogeologists agree that, for all practical purposes, once spilled oil has been introduced into a cavernous carbonate aquifer, only time and nature can take care of the cleanup job.

PIPELINE OIL SPILLS AND THE EDWARDS AQUIFERS

Spill Data in the Edwards Plateau, Hill Country, and Balcones Fault Zone Provinces (1971-1985)

Figure 9 shows the routes of many trunk, petroleum-products, and large gathering-system pipelines in the area of the Edwards aquifers and Hill Country drainage area. In the 27 counties of the subject area, there are 3,867 total line-miles of liquids pipelines (Table 2), consisting of 2,653 line-miles of trunk pipelines having diameters of 6" or larger, 224 line-miles of product pipelines of 4-8"



GENERALIZED GEOLOGIC MAP OF CENTRAL TEXAS

FIGURE 9:

MAJOR TRUNK CRUDE OIL PIPELINES, WITH PROPOSED AND ALTERNATE ROUTES FOR ALL-AMERICAN PIPELINE

PIPELINES IN THE AUSTIN-SAN ANTONIO URBAN CORRIDOR ARE PRODUCT PIPELINES

JULY, 1986 PETER R. ROSE

Table 2. Summary of liquids-pipelines in counties of Edwards Plateau, Hill Country, and Balcones Fault-zone provinces, Texas

COUNTY	TRUNK PIPELINES 6" AND LARGER: MILES	PRODUCTS PIPELINES 4" - 8": MILES	LARGE-AREA GATHERING SYSTEM AND SMALL-BORE PIPELINES: MILES	TOTAL MILES
Bandera	82	0	0	82
Bexar	6	99	20 (est.)	125
Blanco	95	0	0	95
Comal	0	12	0	12
Concho	0	0	0	0
Crockett	335	0	48	383
Edwards	65	0	0	65
Gillespie	121	0	0	121
Hays	68	25	0	93
Irion	73	0	26	99
Kendall	0	0	0	0
Kerr	8	0	0	8
Kimble	163	0	0	163
Kinney	0	0	0	0
Llano	1	0	0	1
Mason	98	0	0	98
Medina	124	0	15 (est.)	139
Menard	9	0	15	24
Reagan	297	0	610 (est.)	907
Real	31	0	0	31
Schleicher	198	0	33	231
Sutton	162	0	14	176
Tom Green	18	0	4	22
Travis	84	36	0	120
Upton	615	52	205 (est.)	872
Uvalde	0	0	0	0
Val Verde	0	0	0	0
TOTALS	2,653	224	990 (est.)	3,867

NOTE: 27 counties included in area.

diameter (mostly in the San Antonio/Austin urban corridor), and approximately 990 line-miles of gathering system and small-bore pipelines (in some counties where oil production is prolific, gathering-system and small-bore pipeline mileage has been estimated).

This pipeline network experienced a total of 1,373 oil spills in the period 1971-1985 (Table 3). Spills larger than 49 barrels of oil numbered 449, and there were 32 spills of 1,000 barrels or larger. The mean spill was 181.3 barrels, and the median spill was 31.5 barrels (Fig. 7, Curve B). The system experienced one spill per 42.2 line-miles per year, considering all spills. For spills larger than 49 barrels, the spill-rate was one spill per 129.2 line-miles per year, and for 1,000-barrel (and larger) spills, the rate was one spill per 1,812.7 line-miles per year (Fig. 8, Curve B). On both Figures 7 and 8, note the close correspondence between Curve B and Curve A (which represents spill frequency for the entire State), indicating that, overall, pipeline spills in the Edwards Plateau, Hill Country, and Balcones fault zone region followed roughly the same patterns as they did for the State as a whole.

However, these data may be misleading for most of the region because there is a disproportionately high concentration of gathering lines and smaller-bore pipelines in the western counties, due to the abundance of oil fields in that area.

Accordingly, Table 4 was prepared as an attempt to focus exclusively on trunk pipeline oil spills in the subject area, since they probably represent a greater potential hazard. Only spills from the six main crude-oil trunk pipelines that cross the region were analyzed. Measurement of pipeline miles is probably more accurate, and spills can be assigned to the source pipeline without question. Twenty-two counties are included in this analysis, containing 1,225 miles of trunk pipelines. There were 33 spills in the 1971-1985 period: 18 were larger than 49 barrels, and 12 were larger than 999 barrels. The mean spill was 2,741 barrels, and the median was 210 barrels. Curve C, in Figure 7, shows dramatically the departure of the crude-oil trunk pipeline spills from populations that contain all types of pipelines: there is a much larger proportion of 1,000-barrel spills from these generally larger-bore pipelines.

Comparison with Statewide Spill Data

Figure 8 compares graphically the relationships of spill frequency by size/class among the following:

1. Statewide data, including all pipelines (Curve A).
2. Data for the subject area, including all pipelines (Curve B).
3. Data for most of the subject area, for larger-bore trunk pipelines only (Curve C).

Table 3. Data From Edwards Plateau, Hill Country, and Balcones Fault-zone Provinces, Texas, All Pipelines

A. Area Pipeline Oil Spills--1971-1985:

Total spills	1,373 = 100.0%
Spills greater than 49 barrels	449 = 32.7%
Spills greater than 99 barrels	292 = 21.3%
Spills greater than 199 barrels	166 = 12.1%
Spills greater than 499 barrels	67 = 4.9%
Spills greater than 999 barrels	32 = 2.3%

Mean spill = 181.3 barrels
Median spill = 31.5 barrels

B. Area Pipeline System (1985):

Crude oil trunk lines	= 2,653 miles
Gathering lines (estimate)	= 990 miles
Product lines	= 224 miles
Total	= 3,867 miles

C. Average Annual Spill-rate For Period 1971-1985:

All spills: one spill per 42.2 line-miles per year

Spills greater than 49 barrels: one spill per 129.2 line-miles per year
Spills greater than 99 barrels: one spill per 198.6 line-miles per year
Spills greater than 199 barrels: one spill per 349.4 line-miles per year
Spills greater than 499 barrels: one spill per 865.7 line-miles per year
Spills greater than 999 barrels: one spill per 1,812.7 line-miles per year

Table 4. Data From Six Main Large-bore Crude Trunk Lines Crossing Area (Excludes Counties With Possible Gathering Systems and Product-lines: Crockett, Irion, Reagan, Upton, and Tom Green Counties, Texas)

A. Area Pipeline Oil Spills (1971-1985):

Total Spills	33 = 100.0%
Spills greater than 49 barrels	18 = 54.6%
Spills greater than 99 barrels	18 = 54.6%
Spills greater than 199 barrels	17 = 51.6%
Spills greater than 499 barrels	13 = 39.4%
Spills greater than 999 barrels	12 = 36.4%

Mean spill = 2,741 barrels
Median spill = 210 barrels

B. Area Pipeline System:

Large-bore crude oil trunk lines included:

Shell (Rancho--24")	217 miles
Exxon (18")	214 miles
Phillips (10")	217 miles
Texas/New Mexico (12")	205 miles
American Petrofina (10")	170 miles
Exxon (12" or 2-10")	202 miles
Total pipeline miles	1,225 miles

C. Average Annual Spill Rate For Period 1971-1985:

All spills: one spill per 556.8 line-miles per year

Spills greater than 49 barrels: one spill per 1,020.8 line-miles per year
Spills greater than 99 barrels: one spill per 1,020.8 line-miles per year
Spills greater than 199 barrels: one spill per 1,080.9 line-miles per year
Spills greater than 499 barrels: one spill per 1,413.5 line-miles per year
Spills greater than 999 barrels: one spill per 1,531.3 line-miles per year

Table 5. Large Spills From Crude Oil Pipelines (01-71 thru 05-86) in Edwards Plateau, Hill Country, and Balcones Fault-zone Provinces, Texas

COUNTY	DATE	OPERATOR	PIPELINE DIAMETER IN INCHES	REPORTED VOLUME	REPORTED RECOVERY BARRELS	REPORTED CAUSE	REMARKS
Crockett	04-10-72	Texas/ New Mexico	12	1,150	120	Human error.	Blown up by gas company dynamite.
	03-31-78	American Petrofina	4	1,296	0	Defective pipe.	None.
	09-15-79	American Petrofina	6	1,719	0	Defective pipe.	None.
	11-06-81	American Petrofina	10	5,600	121	Ruptured pipe.	None.
Gillespie	03-15-77	Exxon	18	1,400	1,185	Corrosion-rust.	1/2" fitting broke off relief line.
Hays	12-14-78	Texas/ New Mexico	12	3,220	3,188	Corrosion-rust.	Reported spill-volume may be low.
Kimble	05-04-79	Exxon	18	25,224	8,730	Corrosion-rust.	Pipe split;see text.
Medina	06-03-71	Exxon	12	1,250	1,050	Pipeline split.	Reported spill-volume may be low.
	07-08-73	Exxon	12	1,300	1,200	Corrosion-rust.	Reported spill-volume may be low. Split joint due to defective pipe.
	01-08-77	American Petrofina	10	3,102	2,700	Prior damage; pressure caused split.	Cold weather congealed oil in earlier shut-down.
	01-21-77	Exxon	12	2,500	1,000	Cold weather--line pulled apart.	None.
Reagan	08-10-72	Exxon	8,10,12 or 18	2,000	480	Corrosion-rust.	None.
	08-02-75	Exxon	8,10,12 or 18	1,000	820	Corrosion-rust.	None.
	11-18-76	Permian Corporation	3	1,834	1,734	Corrosion-rust.	Reported spill-volume may be low.
	04-22-77	Exxon	16	10,500	10,300	Split in lining.	Reported spill-volume may be low.
	07-18-77	Mobil	6	1,500	42	Plow hit line.	None.
	06-28-78	Exxon	26	1,085	1,040	Excess pressure.	Occurred at pump station; reported spill-volume may be low.
	12-22-78	Shell	10	1,900	20	Corrosion-rust.	None.
	01-22-79	Mobil	4	1,000	0	Root plow hit line.	None.
	06-05-81	Western Oil Trans.	6	1,300	900	Company truck ran over line.	Truck impact broke pump and associated fittings.
	08-30-84	Western Oil Trans.	6-1/2	1,880	1,076	Bulldozer cut line.	None.
Sutton	09-28-71	American Petrofina	10	2,526	148	Construction crew cut line.	None.
	06-05-81	American Petrofina	10	2,500	0	Corrosion-rust.	None.
Travis	10-11-76	Exxon	18	2,761	2,100	Bulldozer hit line.	None.
	10-27-79	Exxon	18	1,100	980	Contractor laying water-line, hit with backhoe.	None.
	05-27-86	Shell	24	2,300	2,100	Land developer bulldozer hit line with ripper.	Reported spill-volume may be low.
Upton	08-01-71	Shell	6,8,10,16 or 24	2,044	1,500	Corrosion-rust.	None.
	07-02-72	Exxon	8, 10 or 18	1,300	0	Bulldozer clearing land, hit line.	None.
	03-08-78	Mobil	6	2,060	560	Plow hit line.	None.
	05-21-80	Exxon	18	2,309	1,320	Bulldozer hit line.	None
	05-21-80	Exxon	18	1,500	1,400	Bulldozer cut line.	Incurred while repairing line; reported spill-volume may be low.
	08-27-82	Exxon	8	2,730	130	Equipment failure.	Incorrect operations.
	09-27-85	Shell	6	1,000	900	Corrosion-rust.	Reported spill-volume may be low.

* Excluded from Tables 3 and 4.

** Excluded from Tables 3 and 4--1986 spill.

The pattern again is clear: crude oil trunk pipelines in the Edwards Plateau, Hill Country, and Balcones fault zone region incur small leaks much less frequently than do all pipelines. However, they also incur large spills more frequently than do all pipeline populations. The "crossover" occurs in the 500-1,000 barrel-spill range. For the 15 years ending in 1985, crude-oil trunk pipelines in the Edwards Plateau, Hill Country, and Balcones fault zone region incurred large spills (1,000 barrels of oil and larger) at the rate of about one spill per 1,500 miles of pipeline per year.

Interpretation

Based on the above data, we may anticipate that for the entire 27-county area, there will be about two spills per year of 1,000 barrels or larger. Excluding the five highly drilled western counties, the six main trunk pipelines crossing the pollution-vulnerable central and eastern Edwards Plateau, Hill Country, and Balcones fault zone region should experience one 1,000-barrel spill (or larger) about every 15 months.

It is also important to emphasize that when large-bore pipelines break, larger amounts of oil are spilled. Figure 7 shows that the mean spill size for the trunk pipelines was more than 10 times larger (2,741 barrels of oil) than mean spills for the other populations. Figure 8 shows that large spills occur more frequently in trunk pipelines than in other types of pipelines. Table 6 shows that the median and mean spill sizes of the smaller (10" and 12") trunk pipelines are significantly smaller than for the larger (18" and 24") trunk pipelines in the subject area.

Table 6: Comparison of median and mean spill volumes from smaller (10" and 12") versus larger (18" and 24") trunk pipelines, 22 counties of subject area.

Pipeline Diameter	Median	Mean
10" & 12" (N=24)	120 bbls.	760 bbls.
18" & 24" (N= 9)	1,100 bbls.	3,670 bbls.

It is also noteworthy that causes of pipeline spills for the large-bore trunk pipelines show a different distribution than for all-Texas pipeline spills. Table 5 gives details of all 1,000-barrel and larger oil spills in the affected area. Of the 33 total spills, 33 percent were reportedly caused by corrosion and 36 percent by external sources, such as damage by heavy equipment.

Prior and Future Studies

The question of possible oil-spill pollution of Edwards aquifers was first addressed by Fox, et al. (1976), who restricted their analysis to the area of the Edwards underground reservoir, the adjacent recharge zone in the Balcones fault zone, and the Hill Country drainage area. Fox, et al., utilized a severely limited sample--nine small spills reported from 1970 through 1975 (the largest of which was 200 barrels of oil), and 236.8 total pipeline miles. Unaccountably, they did not include in their data-set two large spills that occurred over the Edwards underground reservoir during the 1970-1976 period: the Exxon pipeline in Medina County suffered a 1,250-barrel spill on June 3, 1971 and a 1,300-barrel spill on July 8, 1973. Fox and his associates correctly noted that the spill-rate for the area of the Balcones fault zone and Hill Country drainage area was much less than the statewide spill-rate, an experience we see duplicated by comparing 15-year spill-rates for the 22-county area versus the statewide spill-rate for the same period. However, because they omitted the two large Medina County spills, they were not able to anticipate that the observed differences applied only to smaller spills having much lower potential for pollution, and that the rate for large spills in the area was similar to, or even larger than, statewide spill-rates.

Utilizing the statewide rates as an alternative, Fox and his co-workers did suggest that there was a high probability of 1,000-barrel and larger spills for time periods of several years or longer in the area of their study. In fact, there have been at least three in the 10 years since their report was published:

1. The 1978 Texas/New Mexico spill of 3,220 barrels of oil in Hays County.
2. The 1977 American Petrofina spill of 3,102 barrels of oil in Medina County.
3. The 1977 Exxon spill of 2,500 barrels of oil in Medina County.

Now that a reliable data base exists with respect to source and location of oil spills in the Edwards Plateau, Hill Country, and Balcones fault zone region, research is underway to document and assess the specific environmental consequences of the 33 large oil spills that have taken place since 1971 (Table 5).

FUTURE PIPELINES - HAZARDS AND REMEDIES

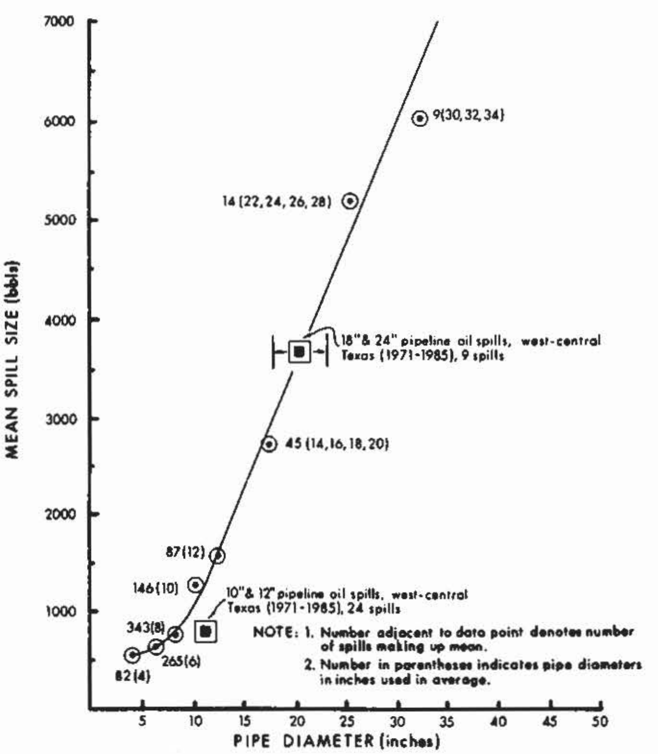
Formal proposals, as well as publicized plans, involved two additional large-bore, high-pressure crude oil pipelines and the Edwards aquifers in 1985 and 1986. The All-American pipeline was planned to cross about 200 miles of the Edwards Plateau aquifer, about 70 miles of the Hill Country drainage area, and, between Austin and San Marcos, about 15 miles of the recharge and confined zones of the Edwards fault zone aquifer. Considerable public concern was expressed (as well as a flurry of lawsuits), focused primarily on protection of the Edwards aquifers from oil-spill contamination. Construction on the second pipeline, the Pacific-Texas (or "Pac-Tex") pipeline has not commenced.

The All-American pipeline is a 30"-diameter, heated crude-oil pipeline which, in August, 1986, was already essentially completed from the California coast near Santa Barbara, across Arizona, New Mexico and trans-Pecos Texas to McCamey, in Upton County. The final 450-mile segment, across Texas (Fig. 9) to refineries south of Houston, would complete the first major U.S. west-to-east oil pipeline, connecting California producing facilities to the rest of the U.S. refining/transportation network. All-American Pipeline Company is an affiliated company of Celeron Corporation, a subsidiary of Goodyear Tire and Rubber Company (All-American is presently being absorbed by Celeron). All-American spokesmen indicated the pipeline was planned to carry low-gravity (i.e., viscous) high-sulphur California heavy crude oil in the 15-20° API gravity range; hence, the need for heating and insulation to facilitate transmission. However, they also acknowledged that the pipeline might carry Alaskan North Slope crude oil, which is approximately 30° API gravity. Considering the proportional magnitude of North Slope versus

California crude-oil reserves--about 7 billion barrels versus perhaps 2 billion barrels--it seems highly likely that Alaskan North Slope crude oil may well constitute a large proportion of future All-American pipeline shipments. Average transmission rates are projected to be about 300,000 barrels per day, at approximately 1,000 pounds per square inch pressure, and maximum rates would be about 450,000 barrels per day. Preliminary plans called for three pumping/heating stations within the subject area, at McCamey, near Sonora in Sutton County, and near Harper in Gillespie County. Average spacing between block-valves is assumed to be 18 miles, based upon the Santa Barbara/McCamey segment (California State Lands Commission, 1984).

Construction across Texas was halted in April, 1986, pending completion of a Supplemental Environmental Impact Statement, in which two alternative routes were also to be considered (Fig. 9): one generally north of the Edwards Plateau, the Llano Uplift, and the northernmost extent of the Edwards underground aquifer, and a second southern route across the western Edwards Plateau, crossing the Balcones fault zone just west of the westernmost extent of the Edwards underground aquifer and then turning east. Final decision on the pipeline route is scheduled for May, 1987.

The second proposed pipeline, the Pac-Tex, is a 42"-diameter heated transmission line, also designed to ship heavy crude, as well as lighter-gravity oil. Construction on this line has not yet commenced, but the proposed route is similar to the All-American pipeline. Company announcements since the All-American controversy indicate the Pac-Tex pipeline is now planned to terminate near McCamey, just as All-American first indicated, before deciding shortly thereafter to extend their pipeline on to the Houston area.



Source: Mastandrea 1982

FIGURE 10: MEAN SPILL SIZE AND PIPE DIAMETER

Projected Spill Volumes and Frequencies

As previously pointed out, oil spills from large pipelines tend to be larger than spills from small pipelines. Mastandrea (1982) presented a graph (Fig. 10) showing the relationship between pipeline diameter and mean spill size. Mean spill sizes for 10- to 12-inch and 18- to 24-inch central Texas pipelines are plotted on Mastandrea's diagram to indicate their general consistency with his results. Based on these data, it appears that mean spill size expected from a 30-inch pipeline is about 6,000 barrels of crude oil and from a 42-inch pipeline about 9,000 barrels.

An independent method by which spill volumes can be estimated is to construct a number of "reasonable scenarios," utilizing a responsible range of values for factors that control spill volumes:

1. Time between rupture and shutdown: 5, 10, 20 minutes (assume half of elapsed time is open flow; half is steadily reducing flow).

2. Shipping rates: 300,000 and 450,000 barrels per day (equals 208 and 312 barrels per minute).

3. Percent of contained oil escaping: 10, 50, 90 percent.

4. Distance between rupture and nearest upstream block-valve: 1, 9, 18 miles.

This approach enables one to gain some perspective as to possible spill-volumes under differing conditions, as well as the relative impact of different variables. It turns out that shutdown time and shipping rate are relatively insignificant, in comparison with percent of contained oil that escapes and distance from upstream block-valves, as factors influencing volumes of oil spilled in pipeline accidents.

Table 7 applies to discrete pipeline breaks, rather than chronic small leaks. It indicates that small, quickly controlled breaks would spill about 500 barrels of crude oil; intermediate spills might be expected to spill about 20,000 barrels; and very large ruptures, located many miles from block-valves, could spill more than 75,000 barrels.

The cross-sectional area of a 42-inch pipeline is nearly two times (1.92) that of a 30-inch pipeline and more than five times that of an 18-inch pipeline. Therefore, to gain a rough idea as to projected losses from a 42-inch pipeline, one can simply double the minimum, "most likely," and maximum scenario-losses excercise in Table 7.

This would indicate that the loss from an "intermediate" 42-inch pipeline spill would probably be a little over 43,000 barrels of crude oil. For perspective, it may be pointed out that, since 1971, the largest recorded pipeline oil spill in Texas, 30,185 barrels, was from a 20-inch pipeline and the second largest spill, 25,224 barrels, was from an 18-inch pipeline.

Based on the above examples, scenarios, and analogies, it appears that oil spills of a thousand barrels or larger may be expected as the rule, rather than the exception, from a 30-inch pipeline, and that it is not unrealistic to anticipate some spills of 20,000 barrels or more. Catastrophic accidents might

Table 7: Scenarios for anticipated oil spills from a 30-inch pipeline, transmitting at 300,000 barrels per day.

Scenario No. 1 (minimum case):

Elapsed time between rupture and total shutdown is 5 minutes.

90 percent of crude oil remains in pipeline.

Rupture is one mile below nearest upstream block-valve.

LOSS .... = 540 barrels

Scenario No. 2 (intermediate case):

Elapsed time between rupture and total shutdown is 10 minutes.

50 percent of crude oil remains in pipeline. Rupture is 9 miles below nearest upstream block-valve.

LOSS .... = 21,591 barrels

Scenario No. 3 (maximum case):

Elapsed time between rupture and total shutdown is 20 minutes.

10 percent of crude oil remains in pipeline.

Rupture is 18 miles below nearest upstream block-valve.

LOSS .... = 77,729 barrels

spill in the neighborhood of 75,000 barrels, or more if not controlled promptly.

If each of the proposed pipelines has the same spill-rate as the six large-bore pipelines reviewed in Table 4, we should expect roughly one spill per year per 556.8 pipeline miles, or about once every two years in its route across the Edwards Plateau, Hill County, and Balcones fault-zone region. Since the median spill from 18- to 24-inch pipelines is 1,100 barrels (Table 6), the expected median spill from each of these proposed very large pipelines would be larger, probably in excess of 2,000 barrels. Accordingly, a spill of more than 2,000 barrels or larger would be expected to occur about once every four years from each pipeline. It should be reemphasized that 1,000 barrels is considered by the writer as the lower threshold of spill size which may have the potential to pollute the Edwards aquifers.

When such spill sizes and frequencies are viewed over perhaps a 50-year pipeline-life, it appears that the occurrence of one or more large oil spills polluting the Edwards aquifers is a probable, rather than improbable, event, whose environmental consequences could be severe and long-lasting.

Remedies

A number of design measures have already been suggested herein, which may serve to limit the quantity of oil spilled in a pipeline rupture. In particular, closer spaced block-valves seem to be an effective improvement. A second improvement concerns the emplacement of a continuous, electronically linked series of hydrocarbon sensors in the pipeline trench, which should greatly assist in locating chronic, or "ghost," leaks. In addition, the construction of barriers and berms to guide spilled crude oil away from especially permeable or sensitive areas along the pipeline route should be considered.

Although clay-lined trenches and large, concrete collection sumps are desirable safety features that would help in containing small, or "ghost," leaks, they do not constitute effective countermeasures against large volumes of heated oil emerging at high pressures. Also, attempts to seal off fractured areas of Edwards outcrop are not only impractical, they would also hinder the natural ground-water recharge process.

Because of the very large volumes of crude oil capable of being spilled from "mega-pipelines," it would seem essential to have continuously maintained and equipped "spill-response stations," staffed by trained personnel capable of being on the scene of pipeline breaks within about two hours of spill occurrence. In the case of the All-American pipeline, prudence would suggest the location of such a "spill station" in the Austin/San Marcos sector, because of its vulnerability and high population density, with another "spill station" located in the Sonora area.

However, all of the above remedies assume that the All-American pipeline will ultimately be built along the originally proposed central route, directly across the Edwards Plateau, Hill Country, and Balcones fault zone. The two alternative routes may offer more appropriate solutions to the problem (Fig. 9). In particular, the northern route appears to be much more attractive, for the following reasons:

1. It avoids most of the Edwards Plateau aquifer, especially the most porous and permeable areas.

2. It avoids all of the especially sensitive Edwards aquifer in the Balcones fault zone in the Austin/San Marcos urban corridor.

3. Along the northern route, from the vicinity of San Angelo to central Mills County, there are no significant or widespread aquifers, and population density is low. In addition, dominantly clayey surface formations there would significantly restrict percolation of spilled crude oil into the subsurface.

4. From central Mills County across Coryell County, the pipeline would cross the Trinity Sand aquifer. This aquifer is much less susceptible to oil pollution than the Edwards aquifers, by virtue of its lower permeability and greater amenability to spill-recovery methods. Also, fewer people rely on the Trinity as a water source.

CONCLUSIONS AND RECOMMENDATIONS

1. There are two "Edwards aquifers" in Texas, one in the Edwards Plateau and the second in the Balcones fault zone area. Both are fractured, cavernous aquifers developed in carbonate rocks that were deposited in very shallow-marine shelf environments. More than a million people in central Texas depend on these aquifers for drinking, agricultural, and recreational water.

2. Because of their exceptional permeability, and the general lack of soil or vegetative cover, the Edwards aquifers are unusually vulnerable to pollution from oil spills. The basic problem is that spilled crude oil flows downward into the bedrock before cleanup crews have time to recover it. Thereafter, such crude oil can move downward to the top of the water table, where it cannot be recovered by mechanical or chemical means.

3. It is estimated that any oil spill of 1,000 barrels or larger probably has a reasonable possibility of reaching the water table in either unconfined Edwards aquifer. Spills of 5,000 barrels, or more, can probably be expected to contaminate Edwards ground water to some degree.

4. Analysis of more than 15,000 spills from Texas oil pipelines, since 1971, provides a reliable basis for assessing frequency and volume of pipeline oil spills. About three percent are spills of 1,000 barrels or larger. The most common cause of large spills is outside-force damage, not corrosion. Human errors and failure of mechanical components are also common causes.

5. In large pipeline accidents, Texas operators generally recover about 40 to 50 percent of the crude oil that was spilled.

6. Expectable environmental damage from crude oil spills includes killed trees; barren agricultural land; contaminated lakes and streams; infertility, illness, or mortality of livestock and wildlife; and contamination of ground water by soluble and insoluble hydrocarbons and heavy metals. Many of these components are highly toxic. Duration of contamination of fresh-water aquifers is expected to be on the scale of years, rather than days.

7. Routes for any newly proposed large-bore trunk pipeline should require approval by the Texas Water Commission, in order to protect sensitive aquifers and surface streams.

8. In the future, selective retrofitting of six existing trunk pipelines in the Edwards Plateau, Hill Country, and Balcones fault zone region is likely to become more desirable in light of the following:

   a. Advancing age.
   b. Increasing population.
   c. Recognition of especially vulnerable zones of the Edwards aquifers.

9. Within the Edwards Plateau, Hill Country, and Balcones fault zone region (excluding the five western oil-producing counties of Upton, Reagan, Crockett, Irion, and Tom Green, where spills will be more frequent), we may anticipate an oil spill from one of these six trunk pipelines about every five to six months; a spill of 1,000 barrels or larger can be expected to occur about every 15 months.

10. Previous studies (Fox, et al., 1976) correctly perceived the lower frequency of all oil spills affecting the Edwards aquifer in the Balcones fault zone and Hill Country drainage area relative to statewide spill-rates, but did not detect that the frequency of large spills was higher than the statewide average, not lower.

11. Based on historical pipeline performance, crude oil spills from a 30-inch pipeline constructed across the Edwards Plateau, Hill Country, and Balcones fault zone can be expected to occur about every two years. About half will probably be greater than 2,000 barrels, and the average spill will be about 6,000 barrels, which is considered to be a polluting spill. Several large oil spills in excess of 20,000 barrels may be expected, and the size of a major oil spill could reach 75,000 barrels or more.

12. Suggested design modifications to reduce spill volumes include closer spaced block-valves; centralized shutdown systems for older lines; electronically linked hydrocarbon sensors; and the construction of barriers to guide spilled crude oil away from sensitive areas. Other measures may be useful in controlling small chronic leaks, but will be ineffective against the heat and pressure of major spills.

13. One or more continuously staffed and equipped "spill-response stations," located near especially vulnerable areas of the pipeline route, can significantly increase the amounts of oil recovered from spills.

14. The suggested northern alternate route appears to represent significantly less hazard to ground water than does the central route across the Edwards Plateau, Hill Country, and Balcones fault zone, proposed originally by the All-American Pipeline Company.

ACKNOWLEDGEMENTS

The writer acknowledges the support of the Travis County, Texas, Attorney's Office and the Environmental Division of the Texas Attorney General's Office. Special appreciation goes to Ms. Barbara Wiley, who drafted the illustrations, and to Ms. Karen L. Rose and Ms. Robin I. Heap for their care in typing and editing the manuscript.

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ROAD LOG

BALCONES ESCARPMENT--SAN ANTONIO TO SAN MARCOS, TEXAS

C.M. Woodruff, Jr.
Consulting Geologist
P.O. Box 13252
Austin, TX 78711

Patrick L. Abbott
Department of Geological Sciences
San Diego State University
San Diego, CA 92182

David H. Riskind
Texas Parks and Wildlife Department
4200 Smith School Road
Austin, TX 78744

mileage	
0.0	Depart San Antonio Convention Center (see fig. 1 for generalized stop locations).
0.1	Turn right onto East Commerce Street; proceed east.
0.3	From right lane of Commerce Street, enter southbound access road to Interstate Highway (IH) 37.
0.6	Merge with IH-37 South.
3.4	Depart IH-37 via exit 138-A--Southcross Boulevard.
3.7	Turn right off of access road.
3.8	Turn right onto East Southcross Boulevard.
4.6	Turn left onto South Presa Street; proceed south.

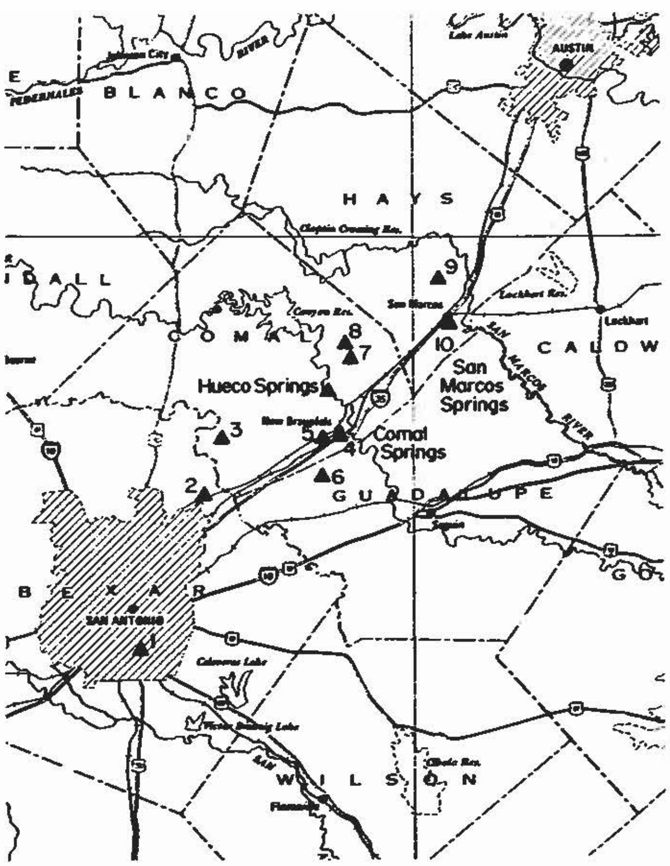


Figure 1. Generalized locations of field-trip stops.

5.0 STOP 1--HOT WELLS HOTEL

This is the site of an abandoned resort hotel, which was built during the 1930's as a spa. Water for the hot baths came from a well that penetrates the bad-water zone of the Edwards aquifer. This well, completed in 1933 to a depth of 572 m (1,876 ft), discharged artesian water at a temperature of 39.4 degrees C (approximately 103 degrees F). Dissolved solids total 4289 mg/L (predominantly calcium sulfate, as reported by Woodruff and others, 1982). The well still flowed as late as 1981. At that time, hydrogen sulfide odor was prevalent, and the well head was coated with a dense growth of algae. Now access to the site is now problematical, and the current condition of the old well is unknown. For a further discussion of geothermal resources along the Balcones escarpment, see Foley and Woodruff (this volume).

Turn around and proceed north on South Presa Street.

5.4 At East Southcross Boulevard, turn right.

6.2 Turn left onto New Braunfels Avenue.

6.4 Turn left on the northbound access road to IH-37.

6.6 Merge onto IH-37; proceed north.

7.9 Cross IH-10 overpass.

On the left is the San Antonio skyline. The city was founded in 1718 when Spanish friars established the first of several missions along the San Antonio River, which is fed by springs issuing along faults in the north-central part of the City. Since the time of earliest occupation by Europeans, the discharge from the Edwards aquifer has sustained the inhabitants of San Antonio (see Palmer, this volume). Today, San Antonio is the largest city in the United States that is dependent entirely on groundwater for its public water supply.

10.8 Merge right with IH-35; proceed north.

19.2 Proceed past Loop 410; continue north.

23.6 Exit onto Loop 1604 (under construction when this log was prepared); mileage is approximate. Cross IH-35 overpass, and proceed west on Loop 1604.

We are approaching the main fault line and escarpment of the Balcones system. On the east side of the fault, bedrock consists of claystones and marls of the Taylor Group (Upper Cretaceous). Deep clayey soils derived from the claystones and marls support facies of Blackland Prairie (mixed to tallgrass vegeta tive stands)--now mostly gone. The mesquite savannah seen here represents some natural vegetative elements, but mostly this assemblage is anthropogenic (that is, man-influenced). Most deep soils on the east side of the fault line have been cultivated for small grains or tame pasture grasses.

When we cross the main fault line, substrate will be Buda Limestone (see stratigraphic section--Table 1). Vegetation changes across the fault line from disturbed prairie to a mixed low woodland dominated by live oak (<u>Quercus virginiana</u>). The oak woodlands occurring on the dissected but gently rolling terrain seen here are also disturbed. The potential natural vegetation adapted to local edaphic (influenced by soil rather than by climate) factors is a live-oak woodland with <u>abundant</u> (that is, solid) ground cover of grasses such as little bluestem, Indiangrass, and the like, as will be seen at Stop 3.

25.5 Cross Missouri-Kansas-Texas (Katy) Railroad tracks.

26.3 Cross Farm-to-Market (FM) Road 2252.

Table 1. General Stratigraphic Section of Cretaceous Units, Balcones Escarpment.

rock unit	characteristics
Navarro Group	Thick section of claystone--Blackland Prairie substrate
Taylor Group	Calcareous claystone and marl--Blackland Prairie substrate
Austin Group	Chalk and marl with local pyroclastic material
Eagle Ford Formation	Shale; local siltstones
Buda Formation	Limestone; not an aquifer
Del Rio Clay	Claystone and shale--forms seal above Edwards aquifer
Georgetown Formation	Nodular limestone--upper part of Edwards aquifer
Edwards Group	Limestone--karstified host rock for Edwards aquifer
Comanche Peak Formation	Marly limestone
Walnut Formation	Hard and soft limestone
Glen Rose Formation	Alternating beds of limestone, dolomite, and marl--numerous small, perched aquifers
Hensel Sand	Sandstone and conglomerate--upper member of "Trinity Sands aquifer"
Cow Creek Limestone	Limestone--locally water-bearing
Hammett Shale	Shale and claystone with sandstone lenses
Sycamore Sand	Sandstone and conglomerate--basal Cretaceous rock unit in Central Texas

26.9 Cross Missouri-Pacific Railroad tracks.

Note the concentration of major rail lines and their proximity to the Interstate Highway. The land along the Balcones Escarpment is an important transportation corridor. Early on, part of the Spanish Camino Real (Royal Highway) lay adjacent to the escarpment. Later, the early cattle drives used the natural topographic break, and the Chisholm trail extended along this line. As public transportation developed, this corridor became the site of stage-coach routes, and later the early State and Federal highways were sited here. Today, the Interstate Highway runs along the escarpment, and there is talk about constructing a high-speed commuter rail system.

27.5 Turn right onto Green Mountain Road.

28.0 STOP 2--HIGH GRAVELS ON CIBOLO CREEK DIVIDE

At this site, we see a section of alluvial gravels perched on the divide between Cibolo Creek and Salado Creek. The gravels consist mostly of limestone fragments, but some chert clasts are also evident. The material was all locally derived--that is, source of the sediment was the Hill Country. Fine-grained fractions of the alluvium have been calichified. The age of this material is unknown. Likewise, the stream that deposited the gravels is unknown. It may have been a former high level of Cibolo Creek, but regional geometrical evidence suggests that Cibolo Creek once flowed to the northeast (Woodruff and Abbott, this volume). Hence, this material may have been deposited either by an ancestral Salado Creek, or by a larger through-flowing stream--such as the Medina River, which is proposed by Woodruff and Abbott (1979) to have had a former, more eastward-directed course.

Proceed straight on Green Mountain Road.

29.1 Turn right onto Evans Road.

29.9 Cross Missouri-Pacific Railroad tracks again.

30.2 Turn left onto Nacogdoches Road (FM 2252).

As we cross Cibolo Creek note that it has no well-defined riparian zone. This is typical of recharge reaches within the Balcones fault zone, because the recurrent high discharge of streams debouching from the Hill Country does not allow establishment of typical riparian assemblages. Vegetation common to the dry creek reaches include Mexican walnut (*Juglans microcarpa*), sycamore (*Plantanus occidentalis*), and buttonbush (*Cephalanthus occidentalis*). Vegetation occurring away from the channel reaches consists of scrub woodland typical of the Edwards uplands (that is, more typical of the western part of the Balcones fault zone), even though we are on the downthrown side of the fault (Pecan Gap Marl of the Taylor Group).

The 37-year average discharge for Cibolo Creek where it is crossed by IH-35 is 14.8 cfs, but it is dry most of the time. Catchment area is 274 square miles. Maximum recorded discharge was 65,000 cfs on 16 July 1973; gage hight was 26.2 ft (U.S. Geological Survey, 1984).

30.5 Cross Missouri-Pacific Railroad tracks again, and proceed past Bracken Road.

31.1 We are at the edge of Cibolo Creek's Quaternary terrace. The bedrock composing the uplands is Austin Chalk.

32.0 Turn left onto Bat Cave Road.

As we proceed north, we are crossing a structurally and stratigraphically complex area of the Balcones fault zone. We are within an area bounded by the Edwards Limestone, but grabens are mapped that result in sections of Buda Limestone and Del Rio Clay being exposed. Vegetation along this part of the route is degraded oak woodlands. This land has been subjected to unwise range management: overgrazing, too many goats, ill-advised burning, and the like.

34.8 Entrance to Bracken Bat Cave.

This cave is the site of the largest concentration of mammals in the world (Texas Nature Conservancy, 1985). Two caves at this locality house 20 to 30 million Mexican free-tailed bats during summer months. These animals eat more than 150 tons of insects (mostly mosquitos) every night. Bat guano has been mined for fertilizer and as raw material for gunpowder, and man-made bat shelters were maintained by early German farmers to tap this renewable source of nitrates.

During late summer, when migrant bats are present, the population of animals in the cave reaches a yearly maximum. They emerge at dusk, and because of their vast numbers their exit from the cave may take as long as six hours. The photograph on the frontispiece records this dramatic evening exodus. The huge flights of bats have posed problems for airplanes from nearby Air Force bases; the animals may be sucked into the intake of a jet engine and then clog the vanes causing a crash. It is reported that the Air Force proposed bombing the caves to alleviate this problem; instead, they altered flight paths to avoid the bats.

35.1 Note catclaw acacia and kidneywood; these are typical South Texas thorn scrub/Tamaulipan thorn woodland species.

35.5 Turn left on FM 3009.

As we proceed northwest we have moved structurally upward (onto the upthrown side of the graben system) and are now traversing Edwards Limestone. This is typical uplands of the Edwards Group within the Balcones fault zone. Most recharge, however, occurs within the major stream reaches. Studies of the water budget in the Barton Springs (Travis/Hays Counties) segment of the aquifer show that approximately 85 percent of incident rainfall is cycled through the biological pump of evapotranspiration (Woodruff, 1984). Approximately 9 percent runs off, and the remaining 6 percent recharges the aquifer. Of this fraction, 85 percent recharges via the major streams, and 15 percent (one percent of total rainfall) recharges on the uplands and in tributary drainageways.

37.6 Entrance to Natural Bridge Caverns; proceed straight.

37.9 Note the overgrazed area inhabited by exotic animals. These exotic species are especially abusive of native range (see Palmer, this volume). On the left, note the browse line in trees created by goats.

38.0 Turn left; continue toward Natural Bridge Caverns.

38.2 Note relatively undisturbed native grass cover. This is probably a reasonable facsimile of what the live oak woodland looked like to original settlers. Such range, with its native grass stands of little bluestem (<u>Schizachinum scoparis</u>) and Indiangrass (<u>Sorgastram nutans</u>), contrasts markedly to the range grazed by the exotic animals.

38.3 Note contrast on two sides of the road: to the left is a native plant assemblage with clumps of oak trees, open grassland, and occasional junipers; to the right is disturbed range--an anthropogenic landscape. Such a disturbed area will have increased erosion and sediment yield. Too, the water budget will be disturbed, with more incident rainfall being allocated to runoff and less to evapotranspiration. Downstream effects on water quality and on periodic flash floods is to be expected but remains unquantified. Disturbances of this type are common across the Hill Country/Edwards Plateau uplands. Also common is the spread of exotic herbivores, which are brought in as tourist attractions (as at the last stop), but are also being introduced as game (trophy) animals. The ecological consequences of this practice is unknown, but as pointed out by Palmer (this volume), Russian boars have become a threatening predator in certain areas.

38.4 STOP 3--NATURAL BRIDGE CAVERNS

Natural Bridge Caverns is the eleventh longest surveyed cave in Texas (Kastning, 1978). It was discovered in 1960 and was opened to the public in 1964.

The cave entrance is within the Edwards Limestone, but most of the passages lie within the Walnut and Glen Rose Formations (Abbott, 1973). Large caverns within the alternating strata of the Glen Rose Limestone are unusual. As suggested by Kastning (1974), the cave may be "inherited" from a previously developed cavern system that occurred along similar trends in the overlying (now removed) parts of the Edwards Limestone. As area-wide base level changed, the water table was lowered, and the cave was thus "incised" into the older, less soluble units.

Passageways within Natural Bridge Caverns are strongly controlled by joint trends. The cave lies along the Bat Cave fault, but the main passages lies at roughly right angles to the strike of this fault. Secondary passages lie parallel to the fault trend (Abbott, 1973; Kastning, 1978). As will be seen as we tour the cave, there are extensive "primary" porosity zones within the Glen Rose strata.

Turn around; proceed back to FM 3009.

39.3 Turn left on FM 3009; proceed north.

39.9 Note that the new road right-of-way is graded fencepost-to-fencepost. This is very bad for the maintenance of native plant species, as seed stock is being lost. Commonly, native seed sources along road rights-of-way contrast markedly with the surrounding vegetation. Roadways are thus important genetic eco-banks. In addition, such indiscriminant clearing and grading exacerbate erosion and downstream siltation.

41.5 Intersect Ranch Road (RR) 1863; turn right and proceed east. We are still traversing Edwards Limestone.

This area is close enough to San Antonio that many of the old ranches have been subdivided into "ranchettes"--weekend homes for urban dwellers. Such use may have a salutary impact, because the lessening of grazing pressure allows recovery of native plant communities (especially the turf-maintaining grasses).

42.4 Note dense stands of juniper (Juniperus ashei). This is commonly a sign of past abuse of the range. Juniper is very "plastic;" it is able to establish itself in shade or in full sun. Potential habitat for juniper is thus maximized owing to human activities. Range fires have been curtailed and removal of thick grasses have combined to abet the increased stands of juniper. Junipers have stomata that are open all the time (unlike those of most broad-leaf plants), thus they consume an extraordinary amount of moisture. Because of this, few plants can become established in the understory beneath the junipers, hence erosion takes place creating ever more habitat for more junipers. In this way, problems beget problems.

A fine discourse on junipers, land use and abuse in Central Texas, and the rise of a distinct breed of Hill Country folk--the "cedar choppers"--is presented in John Graves's Hard Scrabble.

49.7 Intersect Texas State Highway 46; turn right.

51.1 Intersect Loop 336; proceed straight ahead into New Braunfels.

51.6 As we proceed down the Balcones Escarpment, we pass an excellent exposure of Edwards Limestone.

52.3 Turn left, continuing on Texas Highway 46.

52.9 Turn left into Landa Park; cross Comal River.

53.3 Cross Comal River again. Except during periods of rainfall, the entire discharge of this river is from Comal Springs. The average discharge of this river over 51 years is 298 cfs (U.S. Geological Survey, 1984).

53.5 STOP 4--COMAL SPRINGS

Comal Springs compose the largest spring system in Texas and the fifth largest in the U.S. (Meinzer 1927). Long-term average discharge from these springs is 300 cfs; maximum recorded discharge was 534 cfs on 16 October 1973. The springs ceased flowing for a period in 1957 after 7 years of drought (Brune, 1975). Ogden (this volume) has studied the hydrogeochemistry of discharge from individual spring orifices from Comal, Hueco, and San Marcos Springs. This research has demonstrated that different discharge sites within a single spring system may have a markedly different catchment area.

The springs provided water for Indians long before their "discovery" by the French explorer, St. Denis, in 1764. The town of New Braunfels was established in 1845 by German settlers led by Prince Carl of Solms-Braunfels. The springs were a prime reason for their selection of this locality as a settlement site.

Proceed straight; depart Landa Park.

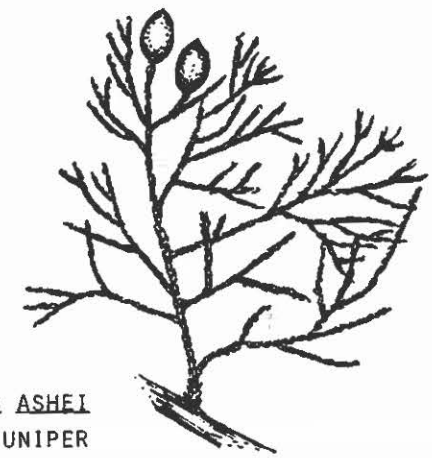
53.6 Ascend the abrupt fault-line scarp.

54.4 Turn left onto Loop 337.

55.5 Proceed beneath Texas Highway 46 overpass.

56.3 On the left is the contact between the Georgetown Limestone and the underlying Edwards Limestone. Both rock units are considered part the Edwards aquifer, although, of the two, the Edwards Limestone is the main water-bearing unit. The lumping of these two units within the aquifer is probably as much a function of the difficulty in areal mapping as it is in the hydrologic properties of the two formations.

Here we see the woody overstory of live oak and juniper trees that are so typical of sloping terrain within the Hill Country/ Edwards Plateau.



JUNIPERUS ASHEI
ASHE JUNIPER

QUERCUS VIRGINIANA
LIVE OAK

56.6 STOP 5--LOOP 337 ROAD CUT

This stop affords an excellent view into the karstified Edwards Limestone along the Balcones Escarpment. Several generations of solution activity are evident here--including Cretaceous collapse and subsequent deposition of undeformed strata, early (perhaps Cretaceous) leaching of selected parts of certain strata producing "boxwork" and honeycomb aspects, and the evident large cavern development including collapses and infilling with terra rossa (see Young, this volume).

Proceed straight on Loop 337.

As we descend the escarpment, we have a dramatic overview of the Blackland Prairie in the distance. We are crossing two grand division of North America (Fenneman, 1931): from the Great Plains (of which the Hill Country/Edwards Plateau is a part) to the Coastal Plains (of which the Blackland Prairie is one part). There are probably few places in the country where physiographic breaks are so abrupt. The fault-based juxtaposition has ramifications on terrain (as seen so dramatically here), on weather and climate (the Balcones Escarpment is the locus of the largest flood-producing storms in the conterminous U.S.), on water regimes (as evidenced by Comal Springs issuing from the base of the escarpment); on soils (Aandahl, 1972); on plants (Riskind and Diamond, this volume); and on animals (Neck, this volume).

57.4 Cross Dry Comal Creek; this drainage system has its headwaters in the Hill Country, but at the escarpment it abruptly changes direction from a prevailing southeastward trend to one of a northeast direction. The implication of this is discussed at the next stop.

58.3 Stop sign; proceed across IH-35.

58.4 Stop again; proceed straight. Note washboard road. This is an indication of insufficient road-base materials being emplaced on the high-plasticity Blackland (vertic) clay soils.

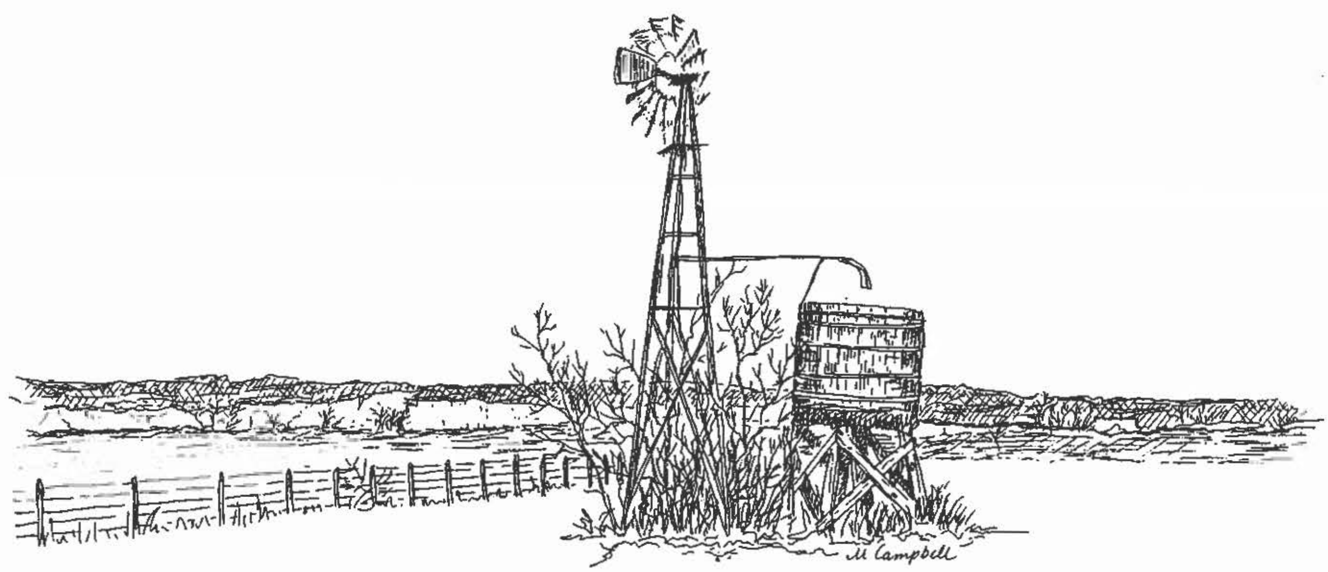
59.0 Turn right.

59.5 Turn left on Santa Clara Road. Note severely overgrazed land on right--a "goatscape."

60.7 Turn right.

61.5 STOP 6--SANTA CLARA CREEK

Here we are viewing a beheaded stream valley. We are near the head of drainage of the southeast-flowing Santa Clara Creek. Note the broad alluvial valley and its proximity to the Balcones Escarpment to the west. This abandoned stream valley and the geometrical relations within the Dry Comal Creek basin (fig. 2), suggest that Dry Comal Creek has eroded headwardly along the Balcones Escarpment, progressively capturing the headwater tributaries to Santa Clara Creek (see Woodruff, 1977). If such processes continue, Dry Comal Creek will eventually capture Cibolo Creek, diverting it from the San Antonio River watershed into the Guadalupe watershed.



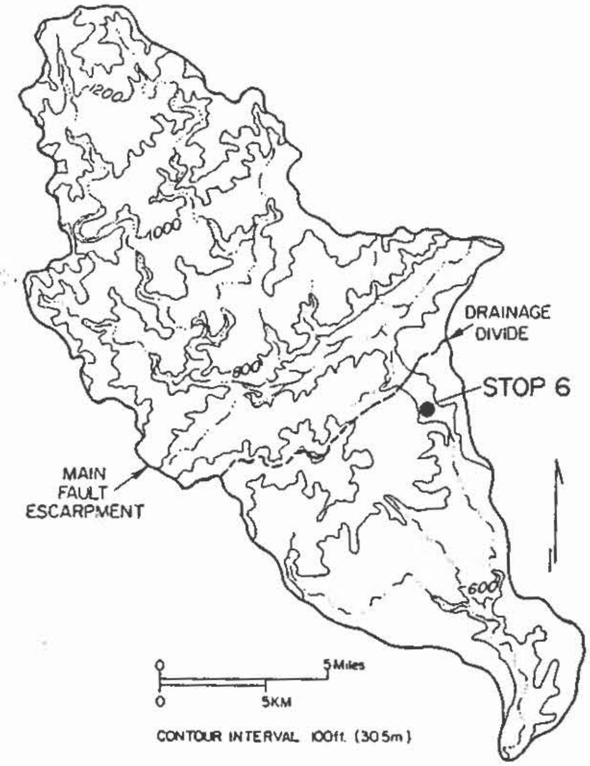
Headwaters of Santa Clara Creek

Proceed straight.

62.5 Turn left onto Marion Road.

63.3 At this high topographic level we are crossing other high alluvial gravels shed off the Balcones Escarpment. This indicates that piracy events were episodic and recurrent.

64.0 Turn right onto Weil Road; the condition of this road clearly indicates the swelling clay substrate.



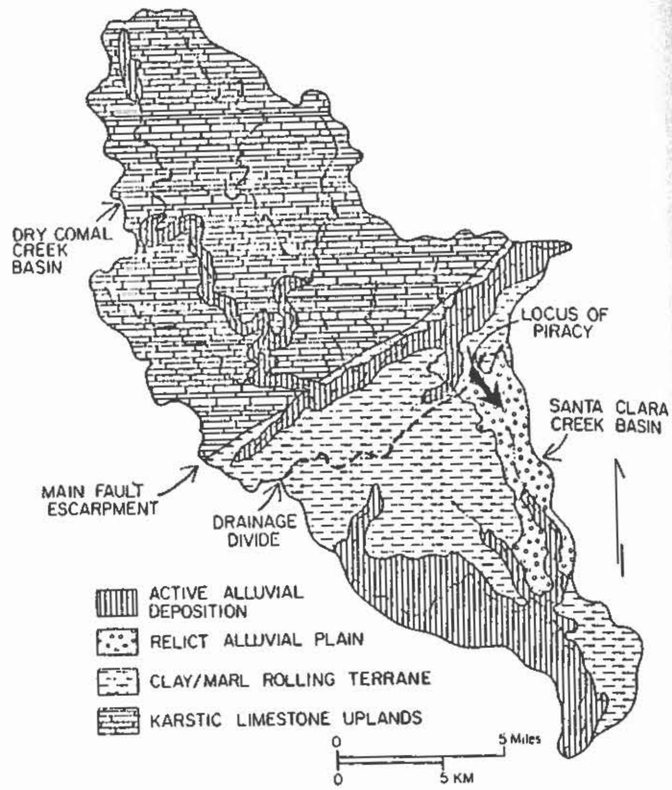


Figure 2. Topographic and geologic maps of Santa Clara and Dry Comal Creek basins (modified from Woodruff, 1977).

64.4	LUNCH STOP--GOERKE'S COUNTRY TAVERN
67.5	Right-angle turn (to left) on Weyel Road.
68.0	Intersect Tolle Road (FM 1103); turn right.
68.4	Brushy areas represent thin soil zones on Pecan Gap Marl. Once this land was open woodland, but it has been disturbed by overgrazing and attempts at plowing and planting. Now a mosaic of brush species occur across the uplands, and willows, hackberry, and elm trees grow along the drainage ways.
70.5	Note the roof tops of a subdivision; this is what is happening along the IH-35 "growth corridor" between San Antonio and Austin. This suburbanization is taking place without regard for the constraints imposed by the bedrock, soils, and processes that occur within the fault zone. Problems include flooding, ground failure, pollution or depletion of surface water or groundwater supplies, septic tank failure, and the like.
71.3	Stop sign; turn right onto IH-35 access road.
71.5	Merge onto IH-35; proceed north. On the left are large quarries that extract stone from the Edwards Limestone. The quarries are of sufficient size that they are clearly visible on Landsat images (sensed from an altitude of approximately 500 miles).
80.0	Cross Guadalupe River; note cypress gallery along river.
83.2	Leave IH-35 via exit 191--Canyon Lake Road (FM 306).
83.5	Turn left onto FM 306; proceed northwest across high terraces of the Guadalupe River.

85.3 We are crossing the main Balcones fault line, which extends along the Missouri Pacific Railroad tracks. We are traversing a mosaic of faulted slices of Edwards, Austin, Buda, and Del Rio Formations. The Escarpment is not expressed in this area owing to the gradual changes in rock type (and hence in erodibilities) across these small-displacement faults, which are part of a ramp structure such as that described by Grimshaw and Woodruff (this volume).

86.0 Note stand of mesquite trees--an indicator of clay substrate (probably Del Rio Clay).

88.3 Note scrub brush indicating shallow soils.

89.5 STOP 7--MEGA-COLLAPSE FEATURE

At this exposure there is a complete section of strata from the upper Edwards to the Buda. The Bat Cave fault runs along the north boundary of this outcrop, but the distortion seen here is not a result of tectonic faulting. Instead, the formations have collapsed into a mega-collapse feature (such as those described by Abbott, 1973). Note that the upper part of the Edwards Limestone is highly fractured and exhibits intensive microkarstification. Farther up the section, the rocks are less competent, and the amount of displacement is less. The result is that the Del Rio-Buda contact is expressed as a broad syncline, that is, a sag into the solution-collapse feature.

Proceed north on FM 306.

90.7 STOP 8--RELICT STREAM CHANNEL ON DIVIDE

Here we see a plano-convex channel cut into the Edwards Limestone. Channel-lag material is clearly evident, although the fine-grained fraction has been calichified. The deposit, as mapped by Bills (1957), extends for about one mile and is as much as 90 ft thick. Clearly we have part of a major fluvial deposit situated on what is now a drainage divide.

This site is situated on the divide between Guadalupe River and Purgatory Creek approximately 330 ft above the present course of Guadalupe River. It is the hypothesis of Woodruff and Abbott (this volume) that this material represents a relict channel of Guadalupe River, before scarp-normal streams captured and diverted the river to its present course.

These relict alluvial deposits support a distinctive vegetative assemblage of post oaks and cedar elms, which contrasts with the prevailing live oak-juniper assemblage that usually dominates the limestone uplands.

91.0 Note terra rossa soil.

92.2 Bear left; stay on FM 306.

93.0 Note collapse feature in Edwards Limestone outcrop.

93.3 Here we are descending rapidly off the Edwards uplands onto the dissected Hill Country below. Bedrock underlying this dissected terrain is Glen Rose Limestone, which consists of a mosaic of lithofacies representing subtidal, intertidal, and supratidal environments. The alternating hard and soft strata of limestone, dolomite, and marl result in the "stair-step hills" characteristic of the Central Texas Hill Country. The basal member of the Glen Rose in this area consists of a massive rudist reef deposit. In that basal part of the section, karst features are common, and the Glen Rose behaves hydrologically similar to the Edwards. For most of the Glen Rose section, however, the limestone and dolomite beds act as small, discrete aquifers separated by marly aquitards. Many wells tap the Glen Rose across the Hill Country, but--except for the lower member (which is localized in geographic extent)--these wells produce water of erratic quality and quantity.

93.9 As we proceed across this dissected landscape, note that the north-facing hills support stands of Spanish oak (Quercus texana); the southwest-facing slopes support more junipers. This is a function of soil microclimate, with the north-facing slopes maintaining cooler temperatures and more soil moisture. The greater insolation on the southern slopes produces a warmer, more arid microclimate that favors junipers with scattered live oak.

94.9 Cross Guadalupe River--the first of many times as we proceed down the "canyon" of the Guadalupe.

95.0 Turn left onto FM 2673; enter the town of Sattler.

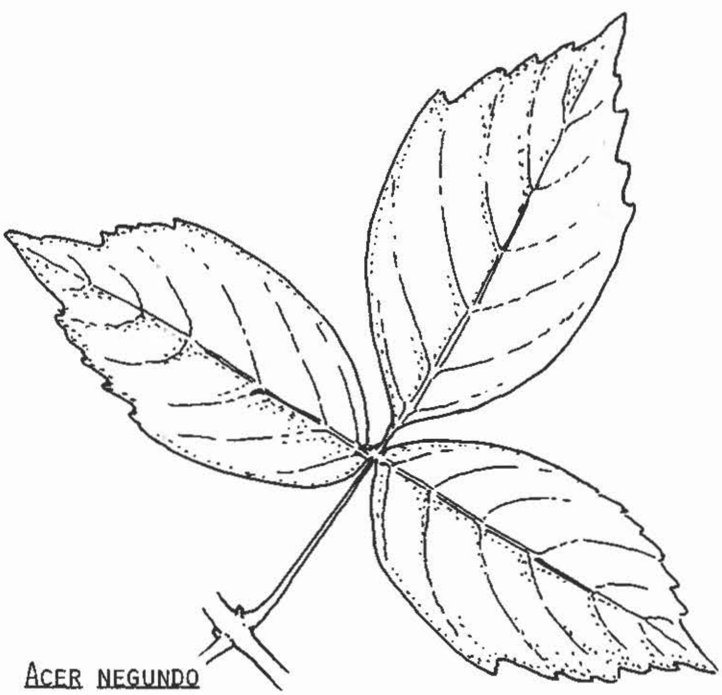
96.5 Turn left onto River Road.

97.1 Cross Guadalupe River. Note how the river valley narrows as we proceed downstream. The incised reaches are presumed to be a response to stream piracy. The relict channel viewed at Stop 8 may be a pre-piracy channel of Guadalupe River. For further discussion of this piracy hypothesis see papers by Woodruff (1977) and Woodruff and Abbott (this volume).

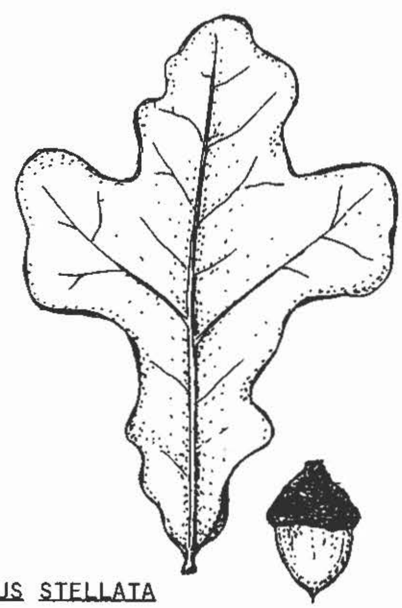
97.8 Note the classic "cedar breaks" on west-facing slope here. Note the dissected, broken, exposed soil. Junipers compose approximately 70 percent of woody vegetation at this locality; most of the remainder consists of various oak species.

98.3 As we drive along the river, the mesic microclimate along the well-watered alluvium supports bald cypress, pecan, ash, box elder, willow, and sycamore. The tributaries have larger bald cypress trees than the main course of the Guadalupe River. This may be because of logging practices as well as periodic destruction of large trees during the occasional catastrophic floods (see Slade, this volume, and Baker, 1975). Clearly, the large trees seen here survived both floods and logging.

98.9 Note the sheer bluffs formed on Glen Rose Limestone. Cedar breaks extend up these dry, steep slopes (a xeric microclimate). Here we have compressed vegetative assemblages, with the riparian woodlands juxtaposed with the xeric associations on the steep slopes. Farther upslope is the gently sloping terrain of the Edwards Plateau.



Acer negundo
Box elder



Quercus stellata
Post oak

101.0 Cross Guadalupe River; note the bald cypress community--all approximately the same age with a few survivors of past floods interspersed. Bald cypress tends to reproduce in stands of equal age. Large floods destroy large stands of adult trees, producing open areas along the floodways. Seedlings can then become established only if there are subsequent periods of low water (droughts even). By looking at the age of stands of trees, one might date major fluctuations in climate--from catastrophic floods to persistent dry periods, during which a "cohort" stand of trees is established.

101.2 Note bluff ahead. There, a complete section of local Cretaceous strata is exposed--Glen Rose Formation in the lower part; Walnut Formation in the middle; and Edwards Limestone at the top.

The upper alluvial terraces have deep, well-drained soils and support large stands of live oak trees. The telescoped plant assemblages that reflect underlying substrate are related to the following geomorphic features: plateau tops and rolling limestone uplands support live oak/juniper; steep slopes and bluffs support xeric assemblages (such as cedar breaks); high terraces support live oak savannah; colluvial slopes/fans support mixed hardwoods with local cedar breaks; and floodplain/channel areas support riparian woodlands.

103.8 Cross Guadalupe River.

105.8 Cross Guadalupe River again.

106.2 ROLLING STOP--HUECO SPRINGS
(also spelled "Waco Springs," as by Bills [1957])

Two springs issue forth from alluvial gravels along the floodplain of Guadalupe River. The source of the groundwater is the Edwards aquifer, and the water rises along the Hueco Springs fault. Maximum recorded discharge from these springs was 131 cfs in 1968 (Brune, 1975). The springs are fed by a limited catchment area, and they commonly stop flowing during dry periods. The springs were dry on 22 April 1986, when this road log was prepared.

The limited catchment area for these springs is illustrated by an observation of Bills (1957). An isolated rainfall during the drought of 1956 produced approximately 5 inches of rain near Smithson Valley, about 12 miles to the west. All surface runoff entered the aquifer where tributaries to Dry Comal Creek crossed the Bear Creek fault. Within 24 hours, Hueco Springs began discharging turbid water at a rate of about 2 cfs.

106.7 As we ascend from the river bottom onto the Edwards Limestone uplands, note the abrupt change to a xeric assemblage of plants. This indicates a warm, dry microclimate owing to thin soil cover, and well-drained bedrock.

107.2 Turn left at the stop sign. We are still traversing Edwards Limestone and typical uplands of the recharge zone.

108.7 Cross Blieders Creek.

Blieders Creek provides an excellent case study of an extraordinary rainfall event and the flooding that occurred as a consequence (this case study is abstracted from Baker, 1975). During the night of 11 May 1972, intense thunderstorms occurred along the Balcones Escarpment near New Braunfels. The center of this storm produced about 16 inches of rain within a 4-hour period, with approximately 75 percent of the rainfall occurring between 2040 and 2140 that night.

The most intense rain fell within the Blieders Creek basin, a 15 square mile watershed, which is tributary to Comal River, which in turn flows into the Guadalupe River. The resulting flood crest (gaged on Comal River) rose 7.5 ft in 15 minutes and 30 ft in 1 hour 45 minutes. The flood that resulted on Guadalupe River is estimated to have a recurrence interval of about 40 years. But this recurrence interval is computed assuming runoff from the entire 1,518 square-mile watershed. In fact, most of the runoff was generated within the 15-square mile Blieders Creek basin. Canyon Dam was designed to protect residents along the downstream reaches of Guadalupe River from floods of this magnitude, but the dam had no effect on this flood event, because the runoff was entirely generated within the 86 square miles downstream from the dam.

109.0 Intersect Texas Highway 46 (Loop 337); turn left.

109.2 Cross Blieders Creek again.

109.3 We are crossing the main Balcones fault line and descending onto Quaternary terraces.

109.8 Cross Guadalupe River.

The average discharge of this river, which drains approximately 1,518 square miles, was 372 cfs between 1929 and 1962 (before the completion of Canyon Dam). Maximum discharge was 101,000 cfs on 15 June 1935; the river ceased flowing at several times during 1956 (U.S. Geological Survey, 1984).

Proceed east on alluvial terrace deposits.

111.7 Intersect IH-35; proceed under freeway.

111.8 Turn left onto north-bound access road.

111.9 Merge with IH-35; proceed north.

115.7 We are now crossing the drainage divide between Guadalupe River and Blanco River. This flat-topped hill is capped with alluvial gravels cemented by caliche (abandoned gravel pits are visible from the highway). Such areas of inverted topography provide evidence for ongoing landscape evolution along the Balcones Escarpment, which is clearly visible on the left.

119.2 Cross York Creek. Here we see a mixture of vegetative assemblages. South Texas brush species, which are limited in their northern extent by winter temperature, are seen here. This indicates that we are in a broad north-south ecotone, just as we have been crossing back and forth across a more abrupt east-west ecological boundary.

126.7 Take exit 204-A to San Marcos.

San Marcos, the county seat of Hays County, was first settled by Europeans when two Spanish missions were relocated here after abandonment of sites established earlier in East Texas owing to difficulties with the Indians and the French. This site was chosen because of the perennial flow of the spring-fed San Marcos River. The town was organized by Anglo-Americans in 1851.

127.0 Turn left onto Loop 82.

127.1 Cross south-bound access road; proceed straight.

127.2 Bear right on LBJ Parkway.

127.3 Turn right on Cheatham Street.

127.6 At stop sign, turn left onto C.M. Allen Parkway.

127.7 Cross Purgatory Creek. The Old Main Building of Southwest Texas State University (SWTSU) occupies the crest of the Balcones Escarpment ahead. SWTSU is the alma mater of former U.S. President Lyndon B. Johnson.

128.1 Cross Hopkins Street; proceed straight.

128.3 Merge with Loop 82 again (now called University Drive); proceed straight.

As we enter the campus area note the "waterscape" on both sides of the road. The San Marcos River is on the right, and a public park occupies the floodplain here. On the left is the SWTSU Drama Department theater; the ponds that grace the grounds are part of a now-discontinued Federal Fish Hatchery. The old hatchery grounds contain 26.6 acres with 12 ponds, 2 long raceways, an artesian well, and various laboratory facilities.

This waterscape owes its presence to the aquifer. The San Marcos River is sustained by discharge from San Marcos Springs, and the hatchery ponds are fed by an artesian well on the grounds of the Edwards Aquifer Research and Data Center, a research branch of SWTSU. This well has been the site of much of the zoological collecting that has allowed the characterization of fauna living within the aquifer waters (see Longley, this volume).

128.5 Intersection with Sessoms Street; the building on the left is the H.M. Freeman Aquatic Biology Building, which houses the Edwards Aquifer Research and Data Center.

Cross San Marcos River; note the water discharging from the weirs on the left. This provides a good visualization of the flow from San Marcos Springs. Mean discharge from the springs is 161 cfs.

The upper San Marcos River contains an unusual assemblage of plants and animals. Many are extremely range-restricted, and some are endemic to this locality. They occur here because of the nutrient availability, constant water flow, and thermal stability of the spring discharge. These factors reflect the vast and intricate underground catchment area of the springs.

Examples of unique plants and animals include Texas wild rice (Zizania texana), and the San Marcos dwarf salamander (Eurycea nana). The river also contains rare finfish, caddisflies, and a giant fresh-water prawn, which can weigh as much as 3 pounds and attain a body length of 12 inches (with antennae extending twice this length). Nearby, from the waters of Ezell's Cave, is the world's only occurrence of the San Marcos blind salamander (Eurycea rathbuni).

128.7 Proceed straight; note good expression of the Balcones Escarpment on the left.

129.2 Pass Aquarena Springs entrance and bear left onto Post Road (immediately before the Missouri-Pacific Railroad tracks).

129.5 Turn left onto Lime Kiln Road. We are crossing the trace of the main scarp-forming fault, but the topographic break is not evident here, as we are traversing the alluvial valley of Sink Creek and Blanco River. This topography is a response to the step faults that compose the northeast block of the ramp structure described by Grimshaw and Woodruff (this volume).

130.4 Cross Sink Creek.

130.5 Note the abandoned lime kiln on left.

131.0 Cross Sink Creek again; note poor expression of its channel. During most rainfall events, flow will be consumed by recharge. But during heavy rains, these channels become the sites of dangerous torrents.

131.7 On right is a quarry, from which stone is extracted from the Edwards Limestone. Also exposed are Georgetown Limestone and Del Rio Clay.

132.1 Turn left onto Hays County Road 222. Note overgrazed range.

133.7 Turn left onto dirt road; proceed to recharge structure.

133.8 STOP 9--SINK CREEK RECHARGE STRUCTURE

This dam was constructed by the U.S. Soil Conservation Service (SCS), as one of a series of similar structures in Hays County designed to enhance recharge into the Edwards aquifer. It rains about 2 percent of the time in the Austin area (Raymond Slade, oral communication, 1985). Most low-order Hill Country streams have very modest base flows, and where they cross the permeable Edwards Limestone, they are dry most of the time. Yet, as already pointed out in this volume, the Balcones Escarpment region has a history of recurrent catastrophic rainfall events and consequent floods. During periods of heavy rains, runoff occurs so rapidly that a relatively small fraction recharges the aquifer. Recharge dams such as the one seen here are designed to catch part of this peak flow. In so doing, more water is recharged, while at the same time a fraction of the surface runoff is detained and does not contribute to the downstream flood hydrograph.

Similar recharge structures are presently in place in the western part of the Edwards aquifer recharge zone--in Uvalde County especially. Some of those structures use sinkholes as actual drains into the aquifer. Medina Lake, northwest of San Antonio was designed as a hydroelectric power source, but a large fraction of its design storage volume infiltrates into the Edwards aquifer.

Presently, a major recharge dam is proposed on Onion Creek to sustain the discharge of Barton Springs in the face of increasing groundwater development in that segment of the aquifer. That proposed structure is designed <u>not</u> to lie directly over the Edwards Limestone but a short distance upstream from the recharge zone. The reservoir thus created would act as a buffer, storing water and meting out a continuous volume of flow that would be within the assimilative capacities of the recharging reaches of Onion Creek.

Turn around; proceed back to San Marcos.

138.1 Turn right onto Post Street.

138.4 Turn right onto Loop 82, and immediately turn right again onto grounds of Aquarena Springs.

138.6 Turn left and proceed to visitor's center.

138.7 STOP 10--SAN MARCOS SPRINGS

Five large fissures and several smaller orifices compose the San Marcos Springs system, second in volume of discharge only to Comal Springs among Texas springs. Spanish explorers located these springs in 1743. The springs provided water supply for the missions sited here and were an important stop on the <u>Camino Real</u>. Later, after settlement by Anglo-Americans, the springs continued to provide water and power for various used and were a major stop along the Chisholm Trail (Brune, 1975). Today the springs are the site of an amusement park and hotel.

These discharge points rise along the main Balcones fault line. These springs have never gone dry during historic times, but discharge decreased to a minimum of about 54 cfs in 1956 (William F. Guyton and Associates, 1979). Maximum recorded discharge was 300 cfs on 5 November 1973 (Brune, 1975). Studies by Ogden (this volume) show that the various spring orifices have distinctively different catchment areas. Some drain the area to the northeast near the Blanco River, whereas others draw on water far to the west.

The spring orifices are now inundated beneath the impounded Aquarena Lake. We will conclude the field trip with a ride on glass-bottom boats in order to view the springs.

	Turn around; proceed back to Loop 82.
139.0	Turn left; cross Missouri-Pacific Railroad tracks, and proceed east to IH-35.
139.8	Turn right onto south-bound access road of IH-35.
140.0	Merge onto IH-35; proceed south.
141.4	Cross San Marcos River.
144.3	Note the nice expression of the Balcones Escarpment on the right. There, Edwards is juxtaposed against Austin Chalk. The Blacklands in this area are so-called chalk prairies (mollisols) instead of being the true blacklands, which are vertisols formed on claystone substrate.
152.8	As we descend from the Guadalupe/Blanco drainage divide, note the excellent view of the Balcones Escarpment behind New Braunfels. As already mentioned, this high divide is underlain by alluvial gravels that are "on grade" with the locus of piracy seen at Stop 8.
157.5	Cross Guadalupe River.
169.6	Cross the drainage divide between Cibolo Creek and Guadalupe River. On right is the rapidly eroding headwater course of Dry Comal Creek--a possible future locus of stream capture.
171.3	Cross Cibolo Creek.
173.3	Pass beneath Loop 1604 overpass.
177.3	Longhorn Portland Cement quarry and plant are on the right; continue straight on IH-35 past Loop 410 interchange.
183.0	Cross Salado Creek.
186.5	Depart IH-35; proceed south on IH-37.
187.8	Leave IH-37 via Commerce Street exit.
187.9	Turn right onto Commerce Street.
188.0	Turn left; proceed to San Antonio Convention Center.
188.2	END OF TRIP.

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EVERGREEN YAUPON

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