GEOLOGY AND HYDROLOGY
OF THE NORTHERN SEGMENT OF THE EDWARDS AQUIFER
WITH AN EMPHASIS ON THE RECHARGE ZONE
IN THE GEORGETOWN, TEXAS, AREA

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EXECUTIVE SUMMARY

In March 1986, the Bureau of Economic Geology was contracted by the Texas Water Development Board to conduct geologic and hydrologic investigations of the northern segment of the Edwards aquifer along the Balcones Fault System in the Georgetown-Round Rock area and in particular to better explain the processes and areas of recharge for the Edwards in the Georgetown area.

Geological mapping in conjunction with analysis of fractures in Comanche Peak, Edwards, and Georgetown limestones (Edwards aquifer strata) in the vicinity of Georgetown and Round Rock, Texas, was done to provide data useful in identifying potential recharge areas and assessment of local ground-water flow, and to increase our understanding of the geology of the Balcones Fault Zone.

Cretaceous Comanche Peak, Edwards, Georgetown, Del Rio, Buda, Eagle Ford, and Austin strata dip gently (1°) eastward and are overlain in some places by terrace deposits and alluvium. Several major normal faults, downthrown to the east, strike northward across the area. Gentle flexures, possibly related to faulting, parallel the faults. Minor normal faults and joints are most abundant in areas adjacent to major faults and flexures. These fractured-strata zones probably parallel the length of the faults or flexure axes and may be as wide as 1.6 km. Most minor faults strike 340°-040°, have displacements less than 2 m, and dip from 40°-80° both eastward and westward. Most joints strike 340°-020° and 260°-300°, and fracture densities range from 4 joints/1 m to 1 joint/5 m in 1- to 2-m-thick beds.

Fractures in the Comanche Peak, Edwards, and Georgetown limestones exhibit both similar and dissimilar characteristics important to ground-water flow. Apertures of fractures in the Comanche Peak and Georgetown limestones are generally less than 1 mm, whereas apertures in Edwards limestones can be several centimeters wide.

Near-vertical joints and minor faults in Comanche Peak and Georgetown strata appear to be common only near major faults or flexures. Major joint sets in all three units have similar strikes, and many of the minor fault planes are filled with calcite. Joints do not have mineral fillings, and abutting relationships suggest minor faults formed before joints.

Faults and joints in limestones of the northern part of the Edwards aquifer probably influence ground water in the same way they do in southern parts of the aquifer. The nonuniform distribution of fractures suggests that the hydrologic characteristics of the aquifer also are nonuniform. Highly fractured areas adjacent to faults should be more permeable than areas farther from faults. For example, springs in Georgetown City Park discharge Edwards aquifer water that may migrate upward through the Georgetown Formation along fractures associated with a major fault 1 km west of the springs.

Evaluation of potentiometric data, continuous water-level-recorder data in conjunction with precipitation data, and hydrochemical data provides a detailed picture of the northern Edwards aquifer as well as identifying possible recharge through the Georgetown Formation.

The potentiometric surfaces for conditions of high flow and low flow indicate a regional flow system that is significantly affected by Balcones faulting along the northern and southern edges of the northern segment of the Edwards aquifer. In the Georgetown area where faulting is less abundant, regional ground-water flow is generally from west to east following approximately the dip of the Edwards Formation. Hydraulic gradients in the eastern part of the Edwards outcrop are steeper than gradients in the confined section to the east and indicate different flow regimes. The western part is characterized by relatively fast ground-water flow circulation, whereas relatively slow ground-water circulation prevails in the eastern part. Main discharge for the shallow, fast flow system occurs along faults and fractures through springs and seeps at the major creeks and rivers in the Georgetown area. Some recharge water moves further downdip past these springs, however, causing large changes in water levels. Discharge from the eastern part presumably occurs through leakage across adjacent formations.

Water levels may respond rapidly to individual rainfall events, depending on the amount of rainfall and previous conditions. Rapid water-level responses in well 58-19-623 located on Georgetown outcrop suggest possible local recharge via vertical flow across the Georgetown Formation. Recharge may be along fractures associated with major faults nearby. Data from continuous water-level recorders provide a method for determining whether a particular location permits recharge or is within a confined section of the Edwards aquifer.

The hydrochemistry of the Edwards water indicates an evolution of ground water from a calcium bicarbonate and calcium-magnesium bicarbonate to a mixed bicarbonate, further downdip to a sodium bicarbonate, and finally to a sodium mixed type water. Tritium concentrations are relatively high in the shallow section, indicating that ground water was recently recharged. This pattern is consistent with the steeper hydraulic gradients in the western part associated with relatively fast ground-water flow circulation. The Del Rio Formation represents the major confining unit for the Edwards aquifer to the east, indicated by a drastic increase in fluoride concentrations and low nitrate concentrations. Ground water beneath the Georgetown outcrop belt is characterized by low fluoride concentrations and relatively high nitrate concentrations. Elevated nitrate concentrations suggest shallow pollutant sources and potential leakage across the Georgetown Formation.

INTRODUCTION--GEOLOGY

In March 1986, the Bureau of Economic Geology was contracted by the Texas Water Development Board to conduct geologic and hydrologic investigations of the northern segment of the Edwards aquifer recharge zone along the Balcones Fault System in the Georgetown-Round Rock area (fig. 1; pls. 1 and 2). The Edwards aquifer is a large underground water reservoir in Central Texas that is contained within Lower Cretaceous Edwards and associated limestones (Klemt and others, 1975; Baker and others, 1985; Woodruff, 1985; Maclay and Small, 1986). The aquifer yields water most abundantly along the Balcones Fault Zone, a major structural break that runs through much of Central Texas between the Edwards Plateau and Gulf Coastal Plain. A growth corridor that in recent years has become the focus of residential, industrial, and recreational development in Central Texas straddles the complex Balcones Fault Zone and recharge zone for the Edwards aquifer. Geological and hydrological investigations of this area have become necessary for guiding urban and industrial development.

The geologic investigations focused on geologic mapping of units cropping out in the Georgetown-Round Rock corridor and analyzing fractures in Comanche Peak, Edwards, and Georgetown limestones. A major part of the mapping studies was the delineation of the Georgetown and Del Rio Formations, which were previously mapped in this area as one unit on the Austin Sheet of the Geologic Atlas of Texas (Barnes, 1974). It is important to differentiate these units because they have different lithologic and hydrologic characteristics. Baker and others (1985) and Slade (1985) consider Comanche Peak, Edwards, and Georgetown limestones to contain the Edwards aquifer in this region. Fractures in the Edwards aquifer limestones may influence the capability of these strata to transmit and hold fluids. Geological mapping and

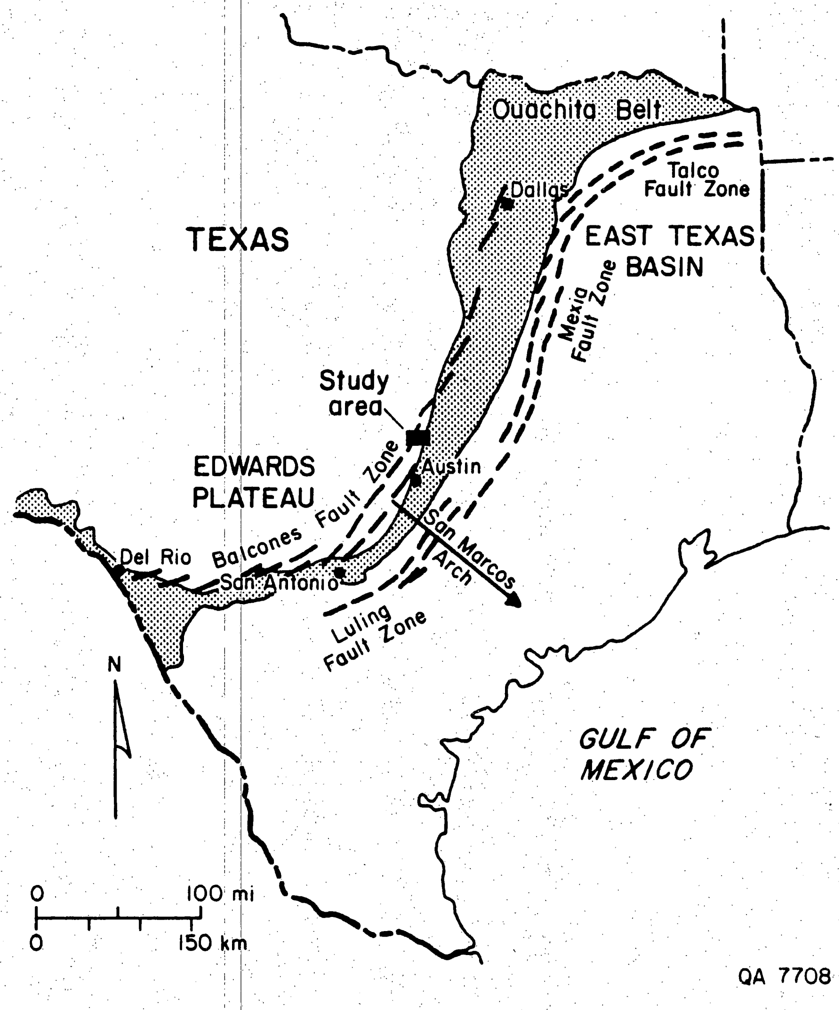

Figure 1. Regional structural setting and location of study area near Georgetown, Texas. Approximate latitude 30°40', longitude 97°40'.

determination of fracture distributions, orientations, and densities throughout the area increase our understanding of the geology of the Balcones Fault Zone and are useful for identifying areas of potential recharge and for assessing ground-water flow in the area. Some aspects of this study may be applicable to other segments of the fault zone and aquifer.

Previous Studies

This investigation benefited from stratigraphic and structural studies done in various parts of Williamson County. They include Marks (1950), Walls (1950), Ward (1950), Tydlaska (1951), Arrington (1954), Atchison (1954), Young (1959 and 1967), Tucker (1962), Rogers (1963), Evans (1965), Martin (1967), Wilbert (1967), and Barnes (1974). These researchers identified and described the units and most of the major faults in the area. Some researchers also noted joint and minor fault trends in parts of the region. These studies provided information necessary to complete the geological and structural mapping and detailed fracture characterization described in this report.

Methods

Field and aerial photographic interpretations were made to complete geologic maps for parts of the U.S. Geological Survey Round Rock, Georgetown, Weir, Hutto, Leander NE, and Leander 7.5-minute quadrangles. Aerial photography used for this study includes (a) 1941 and 1942 Soil Conservation Service black-and-white photography, scale 1:20,000, (b) 1953 Army Mapping Service black-and-white photography, scale approximately 1:65,000, (c) 1974 U.S. Geologic Survey black-and-white photography, scale approximately 1:25,600, (d) 1976 and 1981 Texas Highway

Department black-and-white photography, scale 1:20,000, and (e) 1981 color infrared National High Altitude Photography (NHAP), scale 1:58,000.

Exposures are generally sparse, so much of the aerial photograph and field mapping is based on recognition of different physiographic characteristics of the units. The Comanche Peak Formation (fig. 2) was often identified along river beds by its barren, white, chalky slopes. The Edwards and Georgetown Formations were distinguished from each other by vegetation changes and slight color tonal variations on the color infrared photography. The tonal variations are probably due to slightly thicker soils covering Georgetown rocks. Edwards strata is characterized by rocky summits, rocky and thin soil to no soil, and live and scrub oaks. Georgetown strata is covered by thicker soils than Edwards limestones and supports some live oak growth. Mesquite often grows in the clayey Del Rio Formation. Del Rio clays commonly form steep to shallow slopes below the more resistant Buda Formation. The resistant Buda Formation produces a distinct break in slope that is easily recognized on aerial photographs. The Buda is characterized by thin, rocky soil to no soil, and live oak growth. Tonal variations on black-and-white aerial photographs helped identify the Eagle Ford Formation-Austin Group contact. Soils of both units are cultivated, although in some places Eagle Ford strata support elm and hackberry growth, whereas live oaks generally grow in Austin strata. Quaternary deposits have gentle slopes that aid in their identification on aerial photographs. The rocks and sediments were mapped and studied in the field where exposures occur. Because exposures are generally sparse, surface and aerial photograph mapping was supplemented by interpretations of approximately 80 lithologic and driller's logs.

The detailed fracture investigations were conducted in the vicinity of the San Gabriel River, from Lake Georgetown to the town of Weir (pl. 1). This area was

SYSTEM	SERIES	GROUP	FORMATION	LITHOLOGY
QUATERNARY				Terrace and alluvium sand, silt, clay, and gravel
CRETACEOUS	Upper Cretaceous (Gulfian)	Austin		Chalk, marl, and limestone
			Eagle Ford	Shale and silty limestone to calcareous siltstone
	Lower Cretaceous (Comanchean)	Washita	Buda	Limestone
			Del Rio	Clay
			Georgetown	Limestone and marl
		Fredericksburg	Edwards	Limestone and dolostone
			Comanche Peak	Limestone and marl

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Figure 2. Stratigraphic column for the Georgetown-Round Rock study area.

chosen for the detailed field studies because well-exposed bedrock crops out along the river and its tributaries.

GEOLOGIC, PHYSIOGRAPHIC, AND CLIMATIC SETTING

Lower Cretaceous Comanche Peak, Edwards, Georgetown, Del Rio, and Buda and Upper Cretaceous Eagle Ford and Austin strata crop out and dip regionally 1° eastward across the study area (fig. 1; pls. 1 and 2). East of the North Fork and South Fork (San Gabriel River) confluence and east of Round Rock along Brushy Creek, much of the bedrock is overlain by terrace deposits and alluvium. Several major normal faults, downthrown to the east, strike northerly across the area. Gentle flexures, possibly related to faulting, parallel the faults. The faults are part of the regional Balcones Fault Zone.

Normal faults of the Balcones Fault Zone have an en echelon pattern that extends from Dallas southward to San Antonio, where the zone bends west-southwestward toward Del Rio (fig. 1). This trend closely follows the structural grain of the Paleozoic Ouachita fold and thrust belt (Weeks, 1945). Eastward and parallel to the Balcones Fault Zone are the Luling and Mexia normal fault zones. These fault zones and the Talco Fault Zone of northeast Texas are thought to be related to flexure around the perimeter of the Gulf of Mexico (Murray, 1961). Some fault movement may have begun during the Late Cretaceous, although most of the movement is thought to have occurred during the late Oligocene or early Miocene (Weeks, 1945). Carlson (1984, p. 154-155) reviewed the structure and historical seismicity of Central and East Texas and suggested that faulting of the Balcones system has occurred continuously since the Mesozoic. Reported seismicity that has occurred along the Balcones fault trend may be explained by minor isostatic adjustments due to sediment loading in the Gulf of Mexico (Carlson, 1984).

Corbett (1982) described a "graben-in-graben" style of faulting for the Balcones faults from Dallas to San Antonio and a "horst-and-graben" style of faulting for faults west-southwest of San Antonio. He also determined that fracture intensities in the Austin Chalk outcrop belt within the Balcones Fault Zone are not uniform and areas of high fracture intensities coincide with abundant faulting (Corbett, 1982; Corbett and others, 1987).

The physiography of the Austin area is characterized by the Edwards Plateau, the Rolling Prairie, and the Blackland Prairie (Garner and Young, 1976). In the area north of the Colorado River, the westernmost province, the Jollyville Plateau, represents the undissected portion of the Edwards Plateau of south-central and southwest Texas. Woodruff (1987) described the Jollyville Plateau as the relict outlier of the greater Edwards Plateau, separated by the Hill Country province to the south. The Hill Country province, which is characterized by Glen Rose outcrops, represents a former plateau area dissected by surface streams that eroded most of the Edwards limestone, characteristic outcrop rocks of the Edwards Plateau and the Jollyville Plateau.

The Rolling Prairie is developed within the Balcones Fault Zone, separating the Blackland Prairie to the east and the Jollyville Plateau to the west. South of the Colorado River, the Hill Country province is to the west of the Rolling Prairie, and Edwards outcrop occurs within the Balcones Fault Zone, whereas north of the Colorado River, Edwards outcrop occurs only west of the major fault (northward extension of the Mount Bonnell Fault) on the Jollyville Plateau. Northward into Williamson and Bell Counties, the Balcones Fault Zone becomes less distinct with decreased faulting and less fault displacement across the fault zone. Consequently, the Rolling Prairie loses its particular character and the Jollyville Plateau becomes juxtaposed to the Blackland Prairie in the east; the latter is characterized by outcrops of rocks from the Austin, Taylor, and Navarro Groups. In Williamson County and farther to the north, the Jollyville Plateau is dissected by west-east flowing creeks, becoming similar to the Lampasas Cut Plain terrain to the west and north (Woodruff, 1987).

The drainage divide between the Colorado River to the south and the Brazos River to the north coincides with the Travis-Williamson county line. Therefore, only a relatively narrow recharge zone exists on the Jollyville Plateau for ground water that flows toward the Colorado River. The major creeks in the northern segment of the Edwards aquifer form low-gradient drainage ways within the Brazos River Drainage Basin (Woodruff, 1985).

The climate of the area is subhumid with long, hot summers and short, mild winters. Occasional surges of cold air can cause significant drops in temperatures. In winter, the average temperature is 49°F and the average daily minimum temperature is 38°F. In summer, the average temperature is 83°F, and the average daily maximum temperature is 95°F (Soil Conservation Service, 1983).

Humidity is moderately high and the prevailing winds are from the south. The average annual rainfall for Williamson County, based on measurements taken from 1951 to 1978, is 34.14 inches, of which 60% usually falls in April through September. The general area along the Balcones Escarpment is known for severe thunderstorms that occur predominantly during spring and fall that can cause severe flash floods.

STRATIGRAPHY

As stated previously, stratigraphy in the Georgetown-Round Rock area consists of Lower Cretaceous strata (Comanche Peak, Edwards, Georgetown, Del Rio, and Buda Formations), Upper Cretaceous strata (Eagle Ford Formation and Austin Group), and Quaternary terrace deposits (fig. 2). Lower Cretaceous stratigraphy of Central Texas has been described by many researchers, including Hayward and Brown (1967) and Young (1967). Young (1985) has also studied in detail the Lower Cretaceous Austin Group in the vicinity of the study area.

The Cretaceous rock sequences in the study area reflect several transgressive pulses. The Fredericksburg Comanche Peak and Edwards Formations are transgressive facies representing shallow-marine mud and marl and a reef-lagoon complex, respectively. Georgetown marls and limestones overlie an unconformable Edwards surface and indicate Washita transgression. Regression after Georgetown deposition resulted in deposition of Del Rio clay. The overlying Buda limestone reflects another transgression. Buda strata are unconformably overlain by Upper Cretaceous Eagle Ford shale. Another transgression ended Eagle Ford deposition, and Austin chalk, marl, and limestone unconformably overlie Eagle Ford shale. Quaternary terrace deposits cover Cretaceous bedrock at areas adjacent to streams.

Comanche Peak Formation

The Comanche Peak Formation, a nodular limestone and marl sequence, is approximately 18 m thick in the central part of the study area. The unit thickens northward across the area from about 12 m in the southern part of the area to about 21 m at the Williamson-Bell county line (Young, 1967). The limestone crops out along the North Fork, Middle Fork, and South Fork west of Georgetown and also along Brushy Creek 3 mi west of Round Rock. The contact with the underlying Walnut Formation does not crop out in the study area, although Walnut strata probably are beneath Lake Georgetown. Walnut strata also may be covered by alluvium along the South Fork. Field criteria used to distinguish Comanche Peak and overlying Edwards limestones are based on studies by Ward (1950). Ward (1950) determined the upper contact of the Comanche Peak limestone in this area to be at the top of a thin (approximately 0.3 m) clay to shale bed overlying nodular limestones and marl. The clay to shale bed is overlain by resistant, crystalline Edwards limestone. The regional extent of the upper Comanche Peak clay to shale unit was not determined during this study.

The Comanche Peak Formation has transitional contacts with the Walnut and Edwards Formations. The fauna of this fossiliferous unit has been summarized by Young (1967). The lithology and fauna of the Comanche Peak indicates a widespread, uniform, marine depositional environment (Hayward and Brown, 1967; Young, 1967).

Edwards Formation

The Edwards Formation in the study area consists of a 35- to 50-m-thick sequence of massive to thin-bedded limestones and dolomites. Honeycomb textures, voids in collapse breccias, and cavern systems in Edwards strata are characteristic of the unit and account for most of the significant porosity in the limestones that contain the Edwards aquifer (Abbott, 1973). Chert and rudistids also occur in Edwards strata and are useful for distinguishing Edwards strata from underlying Comanche Peak and overlying Georgetown strata in the field. The Georgetown Formation unconformably overlies Edwards strata, and the top surface of the Edwards commonly has abundant pholad borings (Moore, 1964).

The contacts between the Comanche Peak, Edwards, and Georgetown Formations do not reflect major lithologic changes. Even though porosity is greater within the Edwards sequence, locally the porosity within Comanche Peak and Georgetown limestones may also be high. Mapped contacts between these formations may or may not have hydrologic significance. For example, seeps and springs were commonly observed near the Comanche Peak-Edwards contact between Edwards limestones having greater porosity than Comanche Peak limestones. However, at some localities seeps were observed discharging from Comanche Peak limestones about 20 ft below the Comanche Peak contact.

Georgetown Formation

The Georgetown Formation comprises mostly nodular limestones interbedded with some marls. Georgetown limestones are very fossiliferous; diagnostic marine megafossils include Kingena wacoensis and Gryphaea washitaensis. The unit is 27 to 34 m thick in the study area. These limestones represent the uppermost Edwards aquifer strata. The contact between the Georgetown Formation and overlying Del Rio clay is gradational (Young, 1967).

Del Rio Formation

The Del Rio Formation consists of calcareous, fossiliferous clay that often contains pyrite and gypsum. Exogyra arietina is abundant in the clay. Unweathered Del Rio is composed of kaolinite, illite, and subordinate amounts of montmorillonite. During weathering illite apparently alters to montmorillonite. Weathered Del Rio clay contains only small quantities of illite and greater amounts of montmorillonite (Garner and Young, 1976). Del Rio clay is about 20 m thick in the area. It serves as the confining bed for the Edwards aquifer. The unit is usually poorly exposed in slopes below the Buda Formation. The sharp, conformable contact with the overlying resistant Buda limestone produces a distinct break in slope.

Buda Formation

The Buda Formation in the Georgetown-Round Rock area consists of a lower, slightly glauconitic, fossiliferous limestone and an upper, hard, resistant, burrowed, fossiliferous, shell-fragment limestone (Martin, 1967). The formation thins northward across the area from approximately 8 m to less than 1 m. Buda limestone is absent at several places north of the San Gabriel River (Arrington, 1954). Arrington (1954) interpreted the area where Buda strata is absent to be structurally high. He also interpreted pre-Eagle Ford erosion of the unit. Undivided Quaternary surficial material covers much of the area, so it is also possible that the Buda was eroded from the area during the Quaternary. Arrington (1954) interpreted the structural high to be an anticline, although it is possible that one or more covered faults cross the area.

Eagle Ford Formation

The Eagle Ford Formation consists of a lower calcareous shale, a middle flaggy, silty limestone to calcareous siltstone, and an upper shale. The unit primarily contains montmorillonitic clay. Several thin (1 to 8 cm) bentonite beds may also occur in the middle part of the unit (Garner and Young, 1976). The Eagle Ford Formation is about 20 m thick in the Georgetown-Round Rock area.

Austin Group

The Austin Group, also called Austin chalk, consists of thin to thick bedded chalk, marl, and limestone. Young (1985) has described seven formations in the Austin Group. They are the Atco, Vinson, Jonah, Dessau, Burditt, Pflugerville, and

Sprinkle Formations. These units are not mapped separately. The Austin Group crops out at the eastern part of the study area and is about 130 m thick (Marks, 1950).

Quaternary Deposits

In the Edwards outcrop belt, streams are incised as narrow valleys and Quaternary alluvial deposits are thin and narrow. Downstream of the Edwards outcrop belt, broad alluvial surfaces occur. These alluvial surfaces consist of terraces associated with active streams as well as older remnant terraces.

Quaternary deposits are composed of sand, silt, clay, and gravel. The sediments are mapped as undivided surficial deposits, terrace deposits, and alluvium (pl. 1). Undivided surficial deposits include high terrace deposits, terrace deposits, colluvium, and alluvium that were not differentiated. The surface slopes are generally greater on the undivided surficial deposits than on mapped terrace deposits. The high terrace deposits are thin remnants of older terraces and may reflect paleodrainage. Several terrace levels associated with the San Gabriel River, Brushy Creek, and their tributaries also occur. Alluvium includes deposits in the modern stream channels. Thicknesses of the Quaternary deposits are as great as 11 m and may be thicker in some locations. Some of the undivided surficial deposits at higher elevations are only a few meters thick.

FRACTURE CHARACTERIZATION

Occurrence and Distribution of Faults and Joints

The bedrock or subcrop geology of the study area for the detailed fracture analysis is shown in figure 3. Figure 4 illustrates major faults, flexures, well-exposed

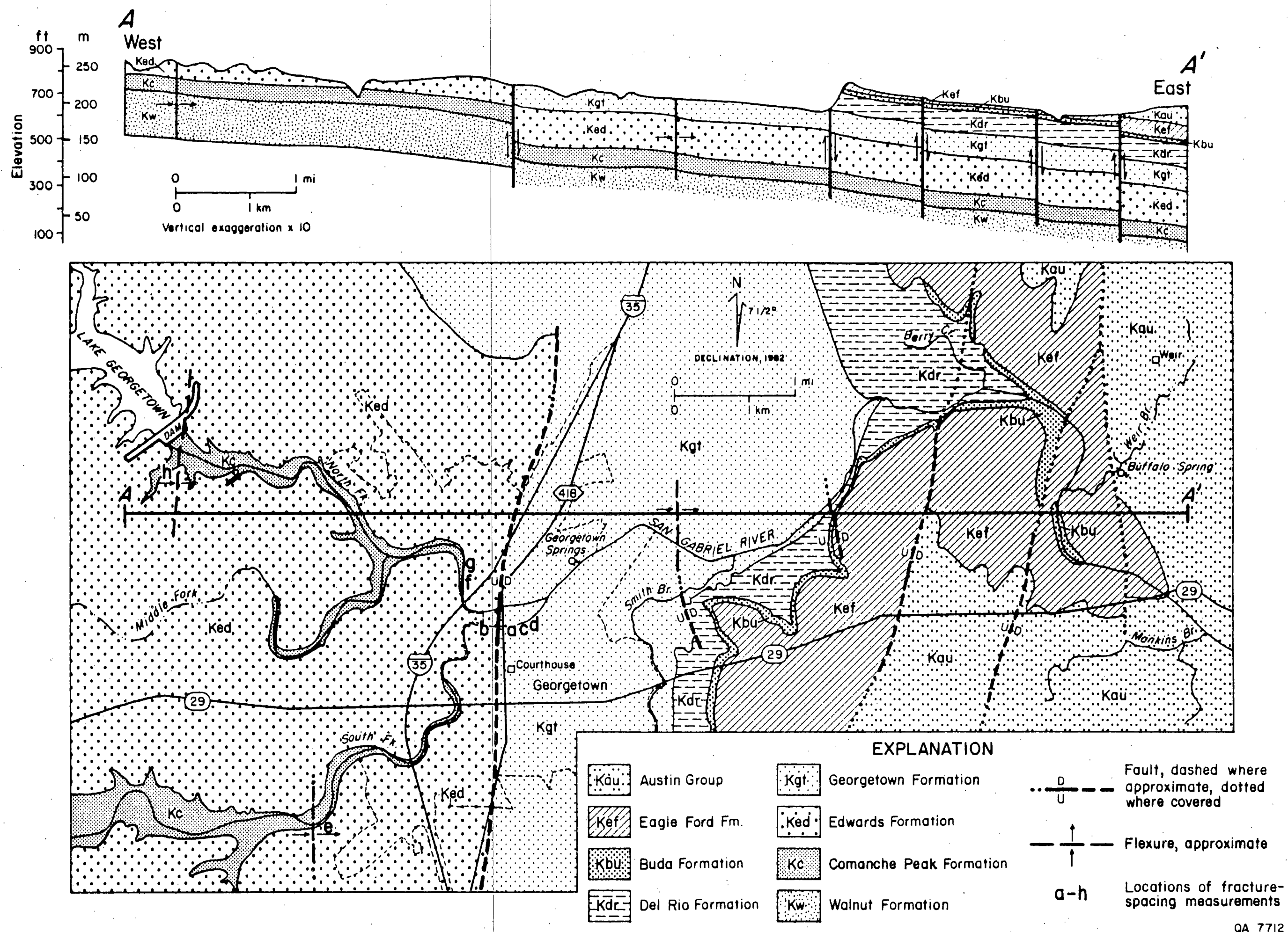


Figure 3. Geologic map and cross section of study area; a through h are localities for fracture-spacing measurements (table 1). Dips of faults in cross section A-A' are unknown.

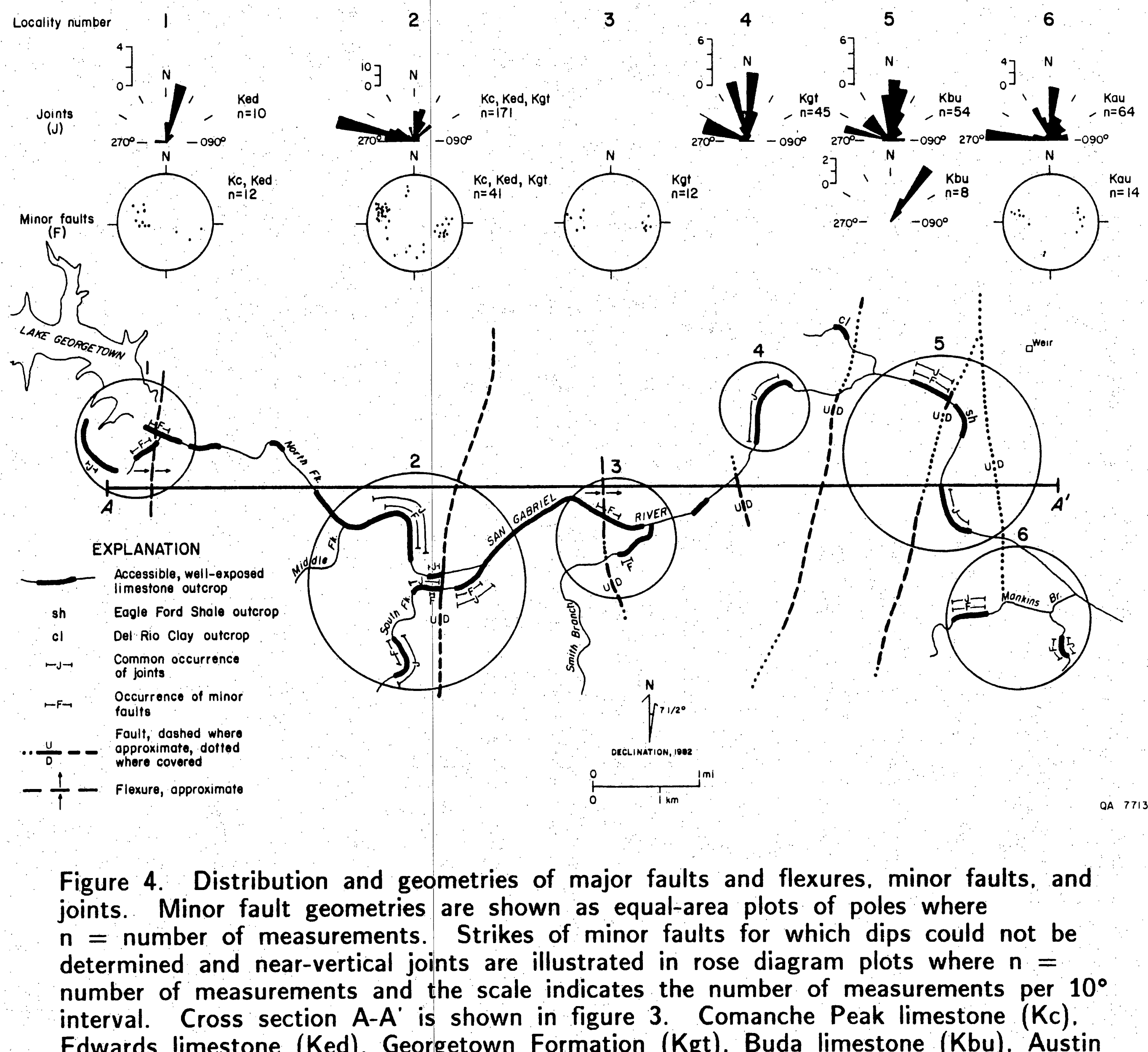


Figure 4. Distribution and geometries of major faults and flexures, minor faults, and joints. Minor fault geometries are shown as equal-area plots of poles where n = number of measurements. Strikes of minor faults for which dips could not be determined and near-vertical joints are illustrated in rose diagram plots where n = number of measurements and the scale indicates the number of measurements per 10° interval. Cross section A-A' is shown in figure 3. Comanche Peak limestone (Kc), Edwards limestone (Ked), Georgetown Formation (Kgt), Buda limestone (Kbu), Austin Chalk (Kau).

limestone outcrop, and the geometries and distribution of minor faults and joints. Major faults and flexures strike northward across the area and are downthrown to the east. Fault planes of major faults are not exposed; however, the faults are thought to have normal displacements on the basis of occurrence of numerous minor normal faults and on the regional structural setting. Major fault displacements are relatively small in this area. The fault at locality 2 (fig. 4) has the greatest throw; it is estimated to be 45 m. Displacements of the other major faults in the area are estimated to be less than 12 m, and some of these faults may actually be flexures with associated faults of small displacements. Poor exposures prevent a better characterization of the major fault geometries. Fault drag was recognized near some faults and appears to have caused beds on the upthrown side of some faults to dip toward the fault plane. It is not known if the mapped fault traces represent single faults or several closely spaced fault splays. Major flexures are gentle and dip less than 10° eastward. Cross faults and flexures that strike subperpendicular to the northward-striking structures were not recognized, probably because of limited exposures in the area. It is reasonable to assume they may exist because some minor faults strike westward (fig. 4) and cross faults have been recognized in other areas along the Balcones Fault Zone (Rodda and others, 1970; Grimshaw, 1976).

Two categories of fractures, minor faults and joints, were studied in outcrop. Field observations along the San Gabriel River and its tributaries indicate that minor faults are most abundant in areas adjacent to major faults and flexures. Even though joints may be in strata throughout the region, joints also appear to occur most commonly near the major structures. The relationship between high joint concentrations and major faults is particularly apparent in Comanche Peak and concentrations and major faults is particularly apparent in Comanche Peak and

Georgetown limestones and less noticeable in Edwards limestones, which appear to be jointed throughout the region.

Minor Faults

Minor faults studied have maximum normal displacements of less than 2 m and commonly displace strata less than 0.5 m. They occur in two sets as indicated by strike direction. Most of the minor faults strike northward 340°-040°, subparallel to the major faults and flexures (fig. 4). These minor faults dip both eastward and westward. Eastward-dipping faults are slightly more abundant in some areas. Other minor faults strike westward 250°-300° and dip both northward and southward. The average dip of minor faults is 55°, although the dips range from 40° to 80°. Slickensides on the minor fault planes indicate slight oblique slip that could be related to rotation of small fault blocks. Rakes are at high angles, greater than 65°, indicating the oblique slip is minor. Approximately 60 percent of the minor fault planes are at least partly filled with calcite. Characterizing minor faults is important because minor faults (1) may act as conduits for ground-water flow, (2) may reflect the nature of poorly exposed major faults, and (3) provide useful information necessary to interpret the age relationships between faults and joints that are discussed later in this report.

Joints

Most joints are near vertical and strike either 260°-300° or 340°-020° (fig. 4). Joints in both of these sets probably can be separated into subsets; however, it is not critical to this investigation. The joint set striking 340°-020° is subparallel to the major faults and flexures mapped across the area as well as subparallel to most of the minor faults. Joints striking 260°-300° are also subparallel to the other minor fault set striking 250°-300°.

Joints in the Comanche Peak, Edwards, and Georgetown limestones exhibit both similar and dissimilar characteristics important to ground-water flow. Apertures of fractures in the Comanche Peak and Georgetown limestones are generally less than 1 mm, whereas apertures in Edwards limestones can be several centimeters wide. Joints occur regionally throughout Edwards limestones, although joints in Comanche Peak and Georgetown limestones are generally more abundant in areas adjacent to major faults. Joints in all three units have similar strikes and are not healed with mineral fillings.

Fracture Spacing

The term fracture spacing in this report refers to the distance between fractures with similar strikes that occur in individual beds. Under ideal conditions, fracture spacing is measured perpendicular to strikes of fractures. Fracture spacing is dependent on bed thickness and rock composition as well as on the amount of tectonic deformation to which the strata have been subjected (Price, 1966; Hobbs, 1967). Studies by researchers in other areas have determined that thicker beds have greater fracture spacing than thinner beds (Price, 1966; McQuillan, 1973). Limestone beds in the Comanche Peak, Edwards, and Georgetown sequence have different compositions; thus, some overlying beds of equal thicknesses may have slightly different fracture spacings. This study indicates that fractures occur throughout the region but are most abundant in areas adjacent to major faults and flexures. The fractured-strata zones probably parallel the lengths of the fault and flexure axes and may be as wide as 1.6 km (locality 2, fig. 4).

The spacing of different fracture sets in Edwards aquifer limestone beds of various thicknesses was determined for this investigation. The number of fractures with similar strikes were counted along traverses 40 to 50 m long in areas adjacent to major faults and flexures (fig. 3). The results of these measurements are given in table 1. Fracture spacing was determined primarily for fractures that strike within the ranges of the two regional fracture sets discussed previously, 340°-020° and 260°-300°. Most of the limestone beds studied are between 1 and 2 m thick. Fracture-spacing values for fracture sets that strike oblique at low angles to traverse directions represent maximums.

This study verifies that fractures are more widely spaced in thicker beds than in thinner beds and that fracture spacing may be different in limestone beds with similar thicknesses. The thickest bed studied is 3.4 m thick and has an average fracture spacing of 8.3 m. An adjacent bed 0.7 m thick and of similar composition is more highly fractured and has an average fracture spacing of 2.2 m. Limestone beds 1.0 to 1.5 m thick have an average fracture-spacing range between 3.3 and 5.0 m. Fracture spacing appears to be about the same for the two regional fracture sets.

Minor faults and joints were combined for this analysis because both types of fractures have the potential to be conduits for fluid movement. The data indicate that these fractures do not occur uniformly in each unit for the different areas studied. For example, minor faults are more common in Georgetown limestones at locations a, c, and d than in nearby Edwards limestones at location b, where joints are abundant (fig. 3; table 1). This relationship could be partly due to rock composition, although the megascopic geometry and nature of the major fault in that area also may be a contributing factor. The faulting style may have concentrated minor faults in specific areas rather than uniformly across the area. At localities where Comanche Peak strata are overlain by Edwards strata, most minor faults cut both units, although some faults terminate in the thicker beds of the Edwards. This

Table 1. Fracture-spacing data measured in Comanche Peak, Edwards, and Georgetown limestones. Measurement localities are shown in figure 2.

Unit[1]	Traverse location number	Traverse strike	Bed thickness	Range in strikes of fractures (faults and joints)	Number of minor faults per traverse length	Number of joints per traverse length	Total number of fractures per traverse length	Fracture spacing (average distance between fractures)
Kgt	a	075°	1.2 m	340°-020°	7/50 m	6/50 m	13/50 m	3.8 m
Kgt	a	075°	1.2 m	260°-300°	0/50 m	5/50 m	5/50 m	10.0 m*
Kgt	c	075°	1.2 m	340°-020°	5/40 m	3/40 m	8/40 m	5.0 m
Kgt	d	070°	1.6 m	340°-020°	7/50 m	5/50 m	12/50 m	4.1 m
Kgt	d	070°	1.6 m	260°-300°	0/50 m	8/50 m	8/50 m	6.2 m*
Ked	b	075°	1.1-1.5 m	010°-030°	0/50 m	15/50 m	15/50 m	3.3 m
Ked	f	355°	3.4 m	260°-300°	0/50 m	6/50 m	6/50 m	8.3 m
Ked	f	355°	0.7 m	260°-300°	1/50 m	21/50 m	22/50 m	2.2 m
Ked	g	005°	1.1 m	260°-300°	4/50 m	7/50 m	11/50 m	4.5 m
Kc	e	050°	1.5 m	340°-020°	1/50 m	15/50 m	16/50 m	3.1 m*
Kc	h	085°	2.5 m	340°-020°	11/50 m	3/50 m	14/50 m	3.5 m

[1]Kgt = Georgetown limestone; Ked = Edwards limestone; Kc = Comanche Peak limestone.
*Maximum average distance between fractures because strike of traverse is oblique to fracture set studied.

relationship may be caused by variations in the mechanical properties of beds of different thicknesses and compositions. There are no exposures of Edwards limestones overlain by Georgetown limestones along the river; thus, the fault relationships between these units could not be verified.

Even though the fracture-spacing calculations indicate an average distance between fractures across 40 to 50 m, fractures are usually not equally distributed. Joints sometimes occur in narrow (1 to 5 m), closely spaced zones (fig. 5). The number of joints per meter (joint density) was measured for closely spaced joints in limestone beds 0.5 to 3 m thick to determine the maximum joint density (minimum joint spacing) that may occur. Figure 6 indicates an average maximum joint density of 3 to 4 joints/m, or approximately 0.3 m between closely spaced joints.

Lateral and Vertical Connectivity of Fractures

Connectivity of fractures is important to ground-water flow studies because it may influence rock permeability and direction of fluid migration. Lateral and vertical connectivity of fractures in this area is difficult to characterize in outcrop because exposures are usually less than 3 m high and strata are only exposed laterally in one direction parallel to the river. Major faults most likely exhibit vertical and lateral connectivity along the fault planes; however, in fractured areas adjacent to or away from faults the fracture connectivity is not as easy to characterize. Field studies indicate that some nearly vertical joints terminate at the upper and lower surfaces of individual beds, whereas others are throughgoing and cut all beds in exposures up to 18 m high. Minor faults exhibit similar characteristics. Field observations

Figure 5. Photograph of closely spaced joints in Georgetown limestone (locality 2, fig. 3). Field notebook is 12 cm wide.

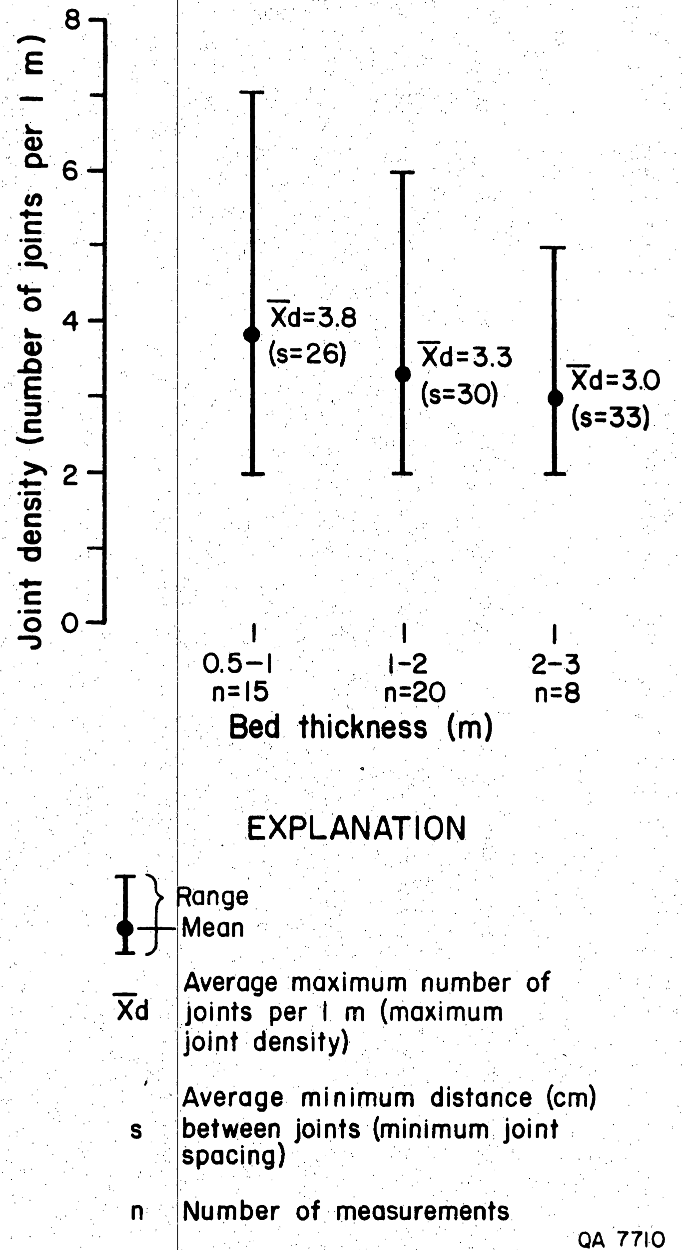


Figure 6. Graph of maximum joint densities in Comanche Peak, Edwards, and Georgetown limestones.

throughout the region suggest that Edwards limestones have a greater potential for fracture connectivity than Comanche Peak and Georgetown limestones in areas away from faults. In areas adjacent to major faults and flexures, Comanche Peak, Edwards, and Georgetown strata may have better fracture connectivity than away from faulted areas. These relationships are based on the frequency in which fractures occur in these units across the area.

The lateral variability of fracture orientations was studied in outcrop adjacent to a major fault at locality 2 (fig. 4). It is assumed that occurrence and strike variability of fractures throughout an area are important characteristics of lateral fracture connectivity. Fractures within sets that are both abundant and continuous across an area have the potential to be connected. The major fault at locality 2 (fig. 4) has a throw of about 45 m, strikes northward, and displaces Georgetown limestones adjacent to updip Edwards limestones. Azimuth versus traverse distance (AVTD) techniques (Wise and McCrory, 1982) were used to analyze variabilities in strikes and occurrences of joints and minor faults measured at exposures in this area (fig. 7). Strikes of these fractures are indicated by the AVTD plots in figure 7. Stations 2 to 40 represent continuous Georgetown outcrop, and Edwards strata are nearly continuous from stations 41 to 64. Station 1 is a small exposure of Georgetown limestone but suggests the major fault trace lies between stations 1 and 41. Because the area between stations 2 and 41 is covered, several major fault splays may occur in this covered area. Joints of the northward-oriented regional fracture set (340°-020°) occur in this area as two subsets. Joints striking 000°-020° are well defined across the faulted area, whereas other northerly striking joints (340°-355°) occur irregularly. Minor faults striking between 330° and 030° are also common in Georgetown strata. The plot (fig. 7) suggests lateral continuity of northward-striking fractures in this area.

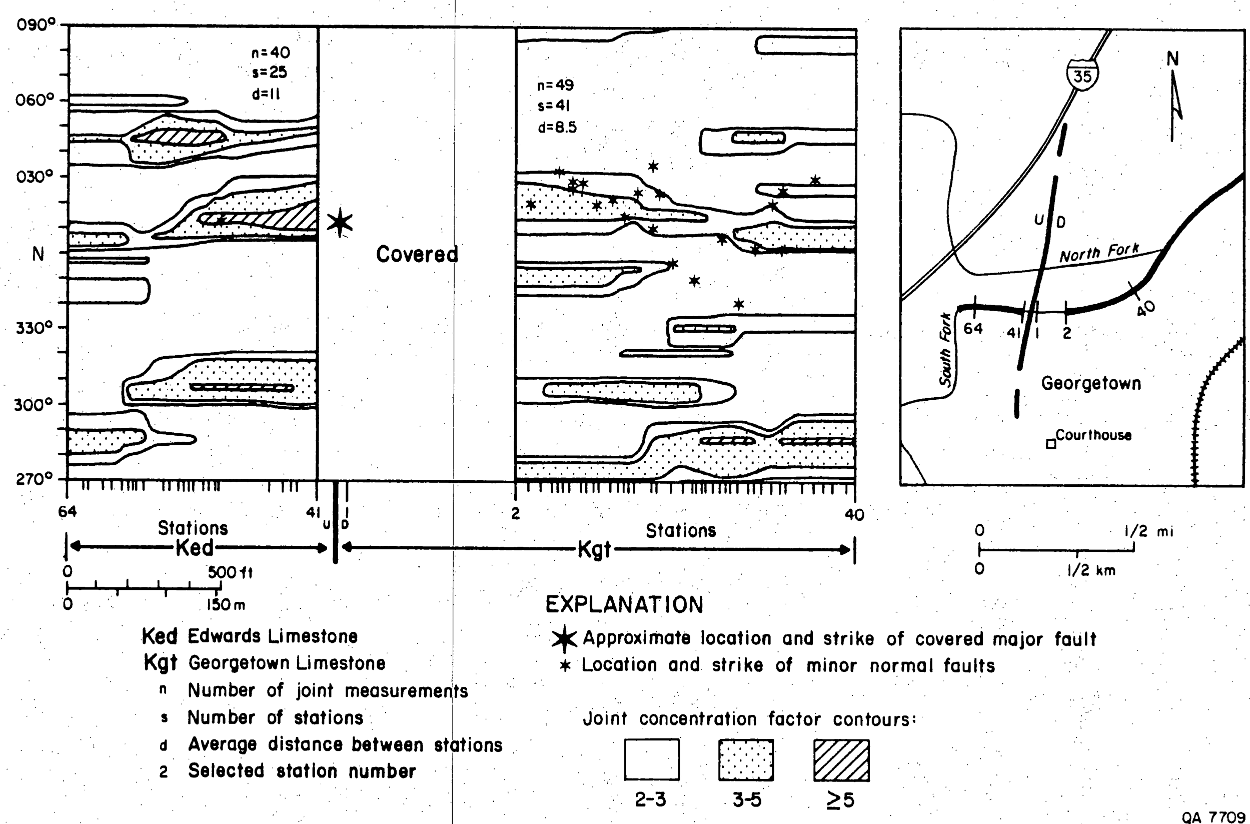


Figure 7. AVTD plots of joints and minor faults in Edwards (Ked) and Georgetown (Kgt) limestones. Contours are in concentrations of data within 10° intervals across every 2° of azimuth (Wise and McCrory, 1982).

Joints striking 260°-300° are well defined on the downthrown side of the fault but occur irregularly along the traverse in the upthrown fault block. Where this joint set is absent, joints striking slightly differently (300°-320°) occur. This relationship suggests lateral continuity of fractures in a west-northwest direction, subparallel to the regional dip and across the major fault plane.

It is unknown why minor faults are more common in Georgetown strata on the downthrown side of the major fault than in Edwards limestones updip. The geometry of the major fault could control the occurrence of minor faults, although variations in limestone compositions and bed thicknesses also may be a factor. In this area Georgetown strata are generally thinner bedded than Edwards strata.

It is unknown if the covered bedrock adjacent to the major fault is more deformed than the nearby exposures. A trench recently dug adjacent to a major fault 30 km south of the study area in north Austin indicates that areas of more intense deformation may occur near faults (fig. 8). The trench, dug during road construction, is approximately 50 m long and trends subperpendicular to a major fault that strikes 020°. The trench exposes Austin limestones that have been down-faulted adjacent to Edwards limestones. Breccias and nearly vertical dipping strata were identified as well as faults and abundant joints striking 000°-030° (fig. 8). The existence of these highly fractured strata verifies the potential of high fracture densities along major fault traces.

Fault and Fracture Relationships

Although detailed analysis of the timing of fractures is beyond the scope of this report, some fracture characteristics provide clues to the general relationships between

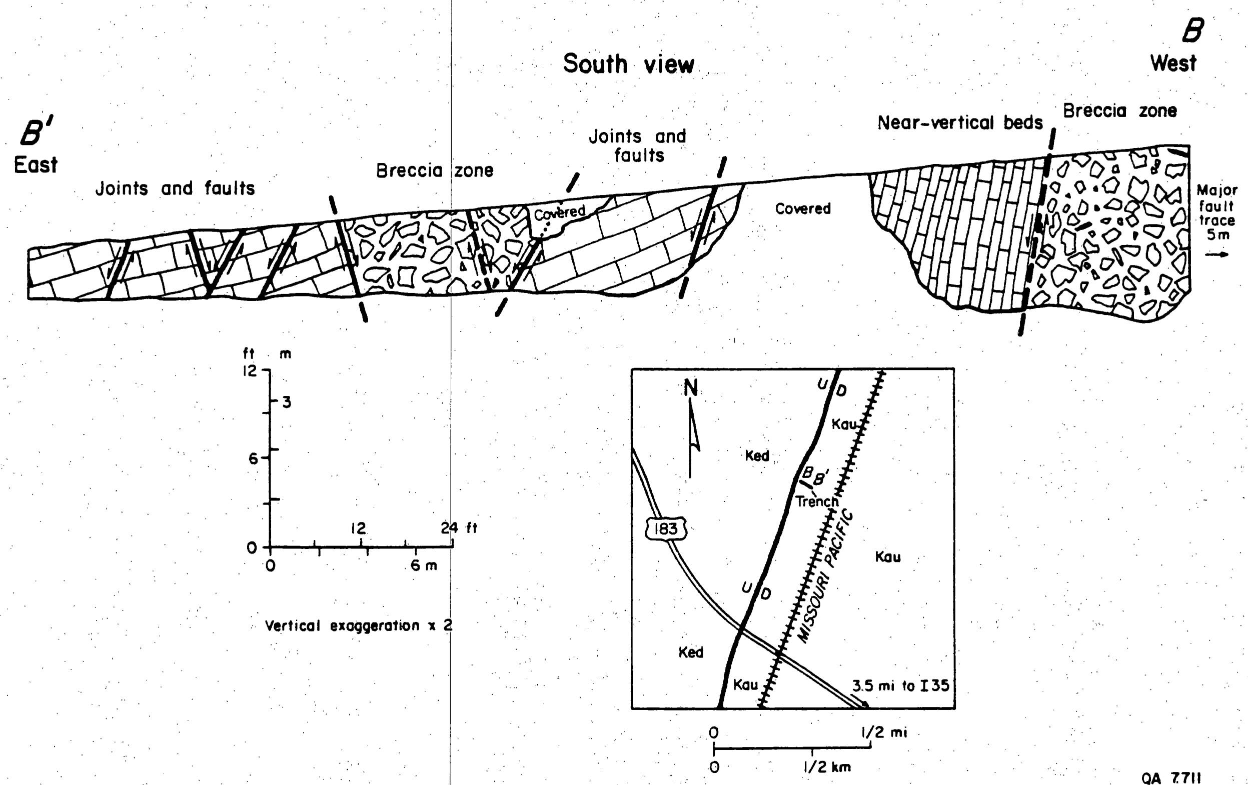


Figure 8. Sketch of deformed Austin Chalk exposed in trench adjacent to major fault in north Austin, Travis County, approximately 30 km south of the study area. Geology of area shown in index map. Edwards limestone (Ked), Austin Chalk (Kau). View is toward the south because strata were best exposed on the south face of the trench.

major and minor faults and joints. The minor faults (identified in outcrops) are presumed to be related to major faults or flexures (identified by field and aerial photographic mapping) on the basis of similarities in strike. Fault geometries and slickensides suggest that regional west-northwest and east-southeast extension developed northerly striking major and minor faults. In addition, cross faults may have formed from slight rotation of the fault blocks. Many of the minor faults are partly to completely filled with calcite; however, the joints have no megascopic mineral fillings. Microscopic analysis of joint surfaces was not done. Abutting relationships indicate joints terminate against the minor faults. Joints of the two regional sets exhibit no preferred abutting relationships. These field observations suggest (1) minor faults formed before joints and (2) joints of the two regional sets formed contemporaneously. The minor faults are tectonic fractures associated with the major faults. The joints may be younger tectonic fractures, or they may be unloading fractures that have formed in response to thermal-elastic contraction accompanying uplift and erosion (Engelder, 1985).

Seeps, Springs, and Fractures

Many seeps and springs occur along the San Gabriel River. West of the North and South Fork confluence, in the Comanche Peak - Edwards outcrop belt, most of the seeps and springs occur from fractures and cavities in Edwards strata or along the contact between the two units, because Comanche Peak limestones usually have lower permeabilities (fig. 9). In the vicinity of Lake Georgetown, springs flowing from this contact appear to be natural discharge points of the Edwards aquifer. However, some seeps and springs occur locally within this area in fractured Comanche Peak strata (fig. 10). One spring identified in this area flows from a cavity in faulted

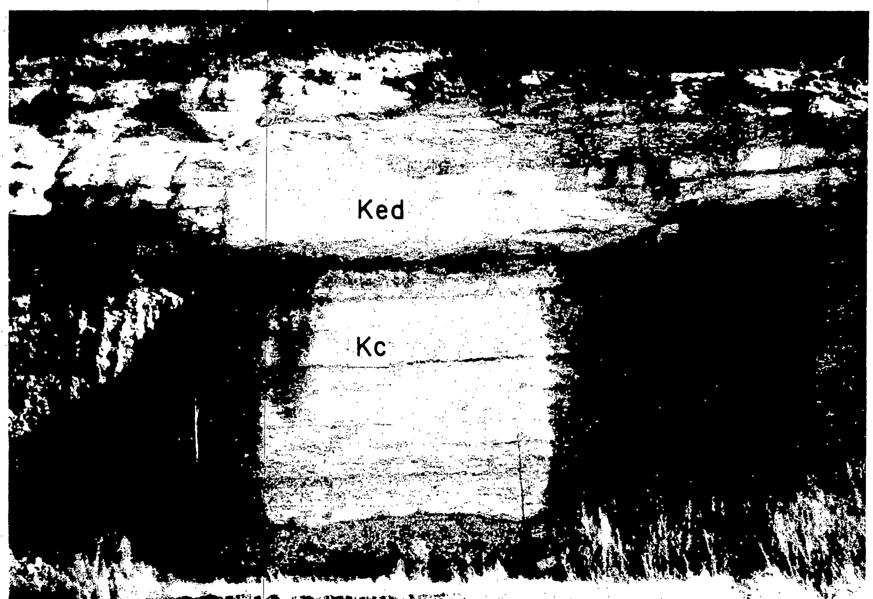


Figure 9. Seeps and springs along contact between Edwards (Ked) and Comanche Peak (Kc) limestones, common in the vicinity of Lake Georgetown.

Figure 10. Seep along minor fault plane in Comanche Peak limestones (locality 1, fig. 3).

Comanche Peak limestone that is 6 m below the Comanche Peak - Edwards contact, indicating that fractured Comanche Peak strata may contain water.

East of the Edwards limestone outcrop belt (fig. 3), seeps and springs commonly occur along the San Gabriel River at the contact between bedrock and terrace deposits. Most of the seeps probably discharge ground water that accumulates by surface infiltration in the porous alluvial sand and gravel. Several springs in Georgetown City Park discharge ground water interpreted to be from the Edwards aquifer (Brune, 1981). This ground water may migrate upward along fractures associated with a major fault that displaces Georgetown limestones adjacent to updip Edwards limestones (fig. 3). The major fault is located approximately 1 km west of the springs. It is unknown why the springs occur 1 km east of the major fault trace rather than directly over the fault. Water may discharge from the major fault plane and then migrate downslope toward the river along the buried contact between the bedrock and terrace deposits. It is also possible that water discharges from fractured strata at the gradational boundary between fractured strata adjacent to the major fault and relatively unfractured strata of lower permeability to the east.

Two other major springs located east of the Edwards limestone outcrop belt in this area are Berry Spring and Buffalo Spring (Brune, 1981). Berry Spring is located on Berry Creek, 4 km (2.5 mi) north-northeast of the Georgetown springs. The spring occurs less than 0.5 km downdip of a major fault covered by terrace deposits and alluvium. This spring also discharges Edwards ground water that has probably migrated upward along fractures (Brune, 1981). Buffalo Spring, located 1.5 km (1 mi) south of Weir on Weir Branch, discharges water from fractures in Austin Chalk. The spring is adjacent to a covered fault that displaces Austin strata against Eagle Ford strata near the surface (fig. 3). Most of the bedrock in this area is covered with terrace deposits. It is likely the spring discharges water that accumulates in the fractured limestone by surface infiltration through the terrace deposits and does not represent discharge of Edwards water.

INTRODUCTION--HYDROLOGY

The northern segment of the Edwards aquifer in Travis, Williamson, and Bell Counties is the northernmost extension of the Edwards Underground Reservoir along the Balcones Fault Zone (fig. 11). The reservoir is an important source of ground water for most counties along the Balcones Fault Zone, which extends southward to Bexar County and continues westward to Kinney County (fig. 11). A ground-water flow divide in southern Hays County divides the aquifer into the Edwards aquifer of the Balcones Fault Zone - Austin Region to the north and the Edwards aquifer of the Balcones Fault Zone - San Antonio Region to the southwest (Muller and Price, 1979). In the Austin area, the Colorado River acts as a hydrologic divide between the southern Barton Springs segment and the northern segment of the Edwards aquifer. Most hydrologic studies to date have focused on the more prolific parts of the Edwards aquifer to the south, the Barton Springs segment and the Edwards aquifer in the San Antonio region. The hydrology of the northern segment of the Edwards aquifer is not well understood in terms of recharge and discharge mechanisms and its hydrochemical characteristics. Urban development in the area, especially the cities of Round Rock and Georgetown, necessitates a better understanding of the hydrology of this part of the aquifer to evaluate the water resource and assess the impact of increased development on ground-water quality.

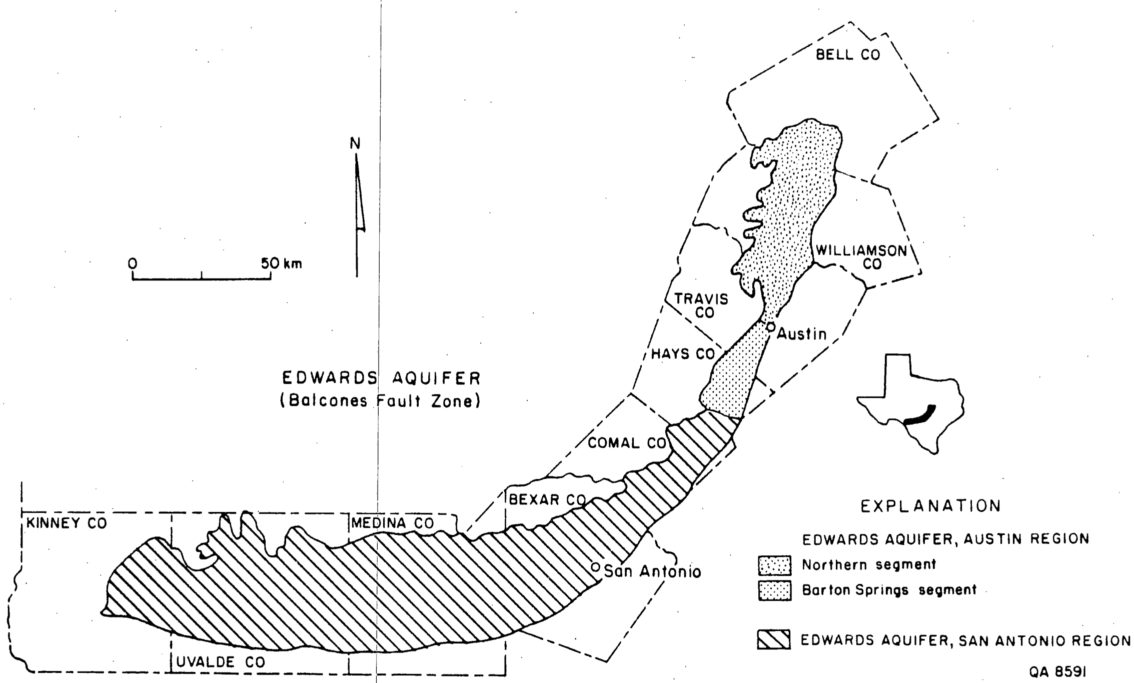


Figure 11. Division of the Edwards aquifer according to the Texas Department of Water Resources (1978).

The hydrogeologic investigation of the northern segment of the Edwards aquifer with emphasis on the Georgetown area was designed, along with the Bureau of Economic Geology's program of geologic mapping of stratigraphy, faults, and fractures, to evaluate the importance of river recharge in the vicinity of Georgetown and to determine whether the Georgetown Formation should be included as part of the Edwards recharge zone as defined by the Edwards order. For this purpose, several approaches were taken: (1) Review existing water-level data to evaluate the important processes for recharge in the Georgetown area. (2) Study water-level variations and precipitation data through time to assess recharge mechanisms. (3) Review existing hydrochemical data to evaluate potential local surface-water recharge, or indications of cross-formational flow. (4) Study water chemistry of selected water samples to characterize the source and determine the age of the water.

Previous Studies

Several geologic and hydrologic studies from various parts of the northern segment of the Edwards aquifer have been reported. These include basic data information on county-wide spring and well inventories for Williamson County (Cumley and others, 1942) and Travis County (George and others, 1941; Arnow, 1957). Evans (1974) gave the first comprehensive hydrochemical study of ground-water in Williamson and eastern Burnet Counties. Klemt and others (1975, 1976) described the hydrogeology on a more regional scale that covered Travis, Williamson, and Bell Counties. They updated the hydrologic data base up to that time and produced various geologic and hydrologic maps.

Brune (1975, 1981) compiled a statewide inventory of springs in Texas and described the major springs in the study area. Snyder (1985) characterized the water chemistry of selected springs on the basis of limited field analyses. Incorporating springs from the Washita Prairie segment of the Edwards aquifer, Yelderman and Collins (1987) discussed the origin of the springs in the area in the context of the particular hydrogeologic setting.

Brune and Duffin (1983) presented a comprehensive study of ground-water occurrences in the Edwards Formation and other water-bearing units of importance in the Travis County area. Baker and others (1986) concentrated on ground-water occurrence in the Edwards aquifer of the Balcones Fault Zone - Austin Region, covering a four-county area from Bell County in the north to Hays County in the south.

Several aspects of the hydrogeology of northern Edwards aquifer segment have been reported in the Austin Geological Society Field Trip Guidebook (Woodruff and others, 1985) and the Geological Society of America Field Trip Guide Book (Yelderman and others, 1987). These field trip guides included papers that dealt with the development of the aquifer as a major water supply (Harriger, 1985), evaluated transmissivity distributions (Slade, 1987; De La Garza and Slade, 1987), analyzed pumping-test data from wells near Pflugerville (Bentley, 1985), and studied the hydrochemistry of Edwards ground water (Clement and Sharp, 1987).

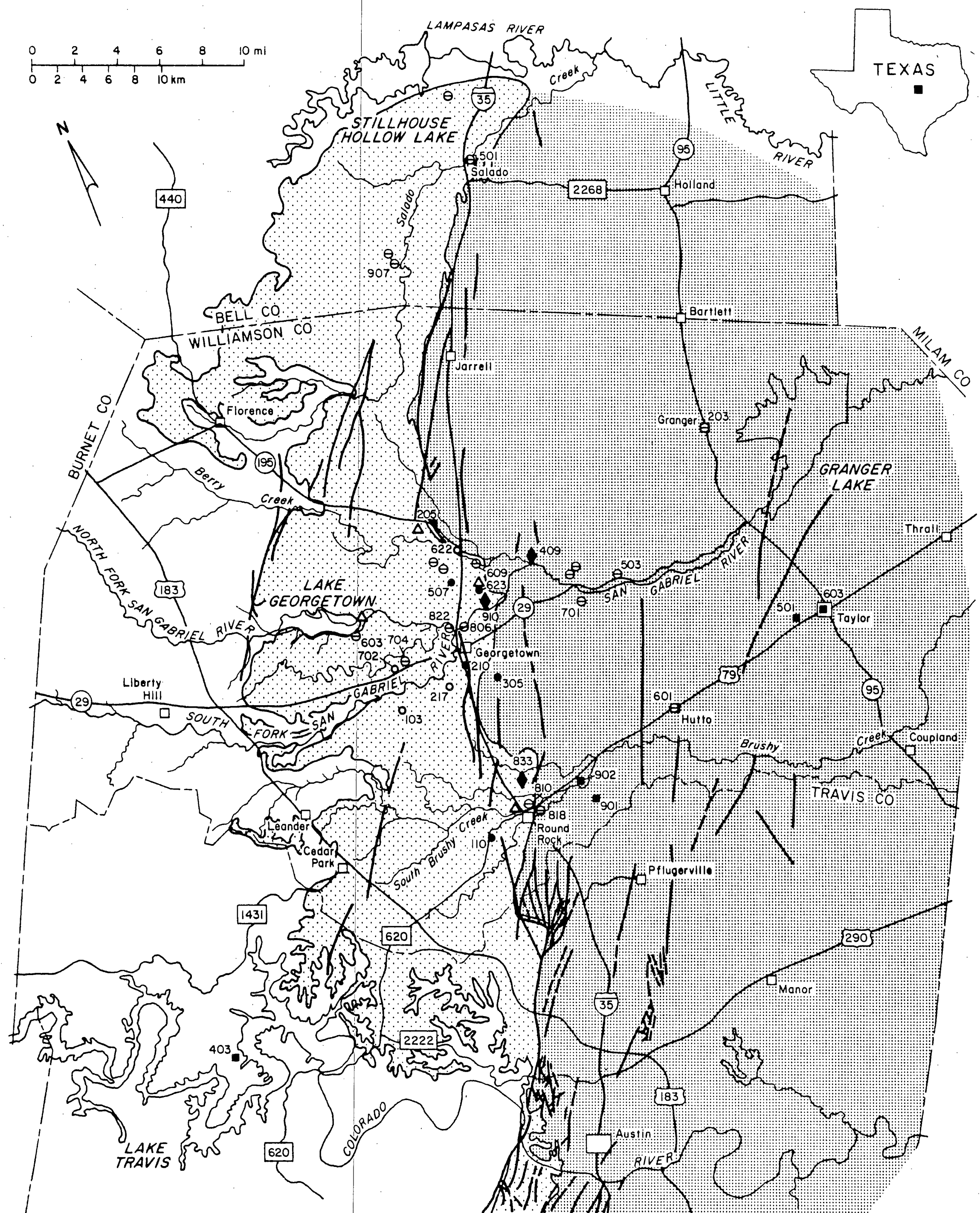
There have been a variety of individual studies by private consulting firms during the past few years addressing the hydrogeology of local areas in the Edwards aquifer. These reports emphasize the potential of the aquifer as a water resource required for urban development in the area. The Texas Water Development Board and the City of Austin both have been conducting investigations dealing with the hydrogeology of the northern segment of the Edwards aquifer.

HYDROLOGIC FRAMEWORK

The northern segment of the Edwards aquifer is bounded to the north and south by hydrologic divides represented by west-east flowing streams, the Lampasas River and the Colorado River, respectively (fig. 12). The land-surface elevations along stream channels represent base-flow elevations of the northern segment of the Edwards aquifer and coincide with major discharge sites. Salado Springs along the northern edge of the aquifer is the largest spring in the northern segment of the Edwards aquifer. Because of the relatively deep incision of the Colorado River to the south, a series of relatively smaller springs issue into the Bull Creek tributary at the contact between the Edwards Formation and the underlying Walnut Formation along the southern escarpment of the Jollyville Plateau. Other smaller springs occur in the confined section of the aquifer, just north of the Colorado River, issuing along faults and fractures (Snyder, 1985).

The fresh-water section of the Edwards aquifer narrows toward the northern and southern boundary. In the central part, the aquifer expands in a west-east direction. The western boundary coincides with the westernmost outcrop of the Edwards Formation, while the bad-water line is generally considered the eastern boundary of the aquifer, east of which total dissolved solids exceed 1000 mg/L.

Ground water from the underlying Trinity aquifers is used primarily in the west, where the Edwards Limestone is absent or too thin to produce significant amounts of ground water. In the area of the Edwards aquifer, ground water from the underlying Trinity aquifers is hardly used. Only in eastern Williamson County, where water quality of the Edwards aquifer deteriorates, ground water from the Lower Trinity aquifer (Hosston Formation) is used as the main water supply for several municipalities.



Geology adapted from Barnes (1974), De Cook (1963), and Garner and Young (1976)

EXPLANATION

- Rocks younger than Georgetown Limestone
- Outcrop of Georgetown Limestone, Edwards Limestone, and Comanche Peak Limestone, which compose the Edwards Aquifer
- 305 Last three digits of well number
- ● Monitor well, continuous recordings
- o Monitor well, weekly measurements
- ■ Well, monthly measurements
- ♦ U.S.G.S. cluster well
- △ Rain gauge
- ⊖ Well or spring with chemical analysis

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Figure 12. Location of monitoring wells and raingauges.

HYDROLOGIC INVESTIGATION

The hydrologic and hydrochemical investigations were designed to evaluate recharge and discharge mechanisms of the aquifer, in particular to determine the importance of local recharge along creeks in the vicinity of Georgetown. Specific hydrologic tasks included (1) review of existing water-level data, (2) construction of potentiometric surfaces of the Edwards aquifer, and (3) study of water levels and rainfall through time.

Two regional potentiometric surfaces were constructed, showing (1) low-flow conditions based on water-level measurements obtained during relatively dry years and (2) high-flow conditions based on measurements during relatively wet years. For the low-flow conditions, water-level measurements primarily from the last two extensive dry periods in 1978 and 1984 were used; in case data coverage was sparse for certain areas, measurements from earlier dry years, for example, 1967, 1956, 1955, 1944, and 1939, were used. For high-flow conditions, measurements during relatively wet years in 1979 and 1981 were used. In addition, available measurements from other wet seasons were included when needed.

The constructed potentiometric surfaces were compared with streamflow measurements conducted by the U.S. Geological Survey in 1978 and 1979 (Baker and others, 1986), to correlate stream losses and land-surface elevation with the constructed potentiometric surfaces.

Individual water-level hydrographs from the area based on approximately monthly measurements were studied to further describe the seasonal variations and extent of water-level variations of the aquifer. Examination of these hydrographs allowed us to use measured water-level data from different periods to construct potentiometric surfaces, documenting the hydrodynamics of the aquifer. Note that some scatter of water-level data is implicit in these potentiometric surfaces. On the other hand, by interpreting data from different periods, data coverage is greatly increased and potential conflicts in measurements can be resolved.

Detailed field investigation involved a water-level monitoring network (table 2). Five continuous water-level recorders were installed in selected wells in the area (fig. 12) to investigate in greater detail water-level variations in response to individual recharge events, as recorded by precipitation data. The following wells were monitored using Stevens water-level recorders: wells 58-35-110, 58-27-210, 58-19-507, 58-19-205, and 58-19-623. In addition, water levels in several wells were measured on a weekly basis; these include: wells 58-27-103, 58-27-217, 58-19-702, and 58-19-622.

Other continuous water-level measurements were available from well 58-27-305, operated by the Texas Water Development Board (TWDB) southeast of Georgetown since 1981. The U.S. Geological Survey District Office in Austin has been monitoring water levels in three cluster-well sites that were drilled by TWDB in the area (fig. 12).

Water-level variations in these wells were compared with precipitation data from official rain stations of the National Weather Service, from municipal raingauges in Round Rock and Pflugerville, and from a raingauge operated by the Lower Colorado River Authority in northern Travis County (fig. 12). In addition, two raingauges were installed near wells 58-19-205 and 58-19-623 to continuously measure amounts and rates of precipitation.

The investigation of detailed water-level patterns for the different Edwards wells is designed to characterize recharge and discharge mechanisms of the Edwards aquifer. Furthermore, on the basis of these characterizations, implications of potential flow through the Georgetown Formation are derived.

Hydrochemical investigations included (1) review of existing hydrochemical data and (2) analyses of water chemistry from selected samples. The purpose of the hydrochemical study was to evaluate potential local river recharge or subcrop recharge from formations beneath the Edwards Formation. Water chemistry data were evaluated to identify possible correlation between changes in water chemistry and water levels that would indicate rapid recharge events.

For this purpose, water chemistry and water types for the Edwards, Glen Rose, and Hosston Formations were characterized and compared with each other to better explain the hydrology of the system. For the Edwards aquifer, the geographic distribution and total dissolved solids were evaluated in light of the overall hydrogeologic setting.

During this study, several water wells and springs were sampled (table 2). Besides analyzing for major cations and anions, minor elements such as fluoride and strontium were analyzed to better characterize sources of ground water. Tritium analyses were performed to determine absolute and relative ages of ground water in the area. Two springs were repeatedly sampled before and after major rainfall events to identify possible changes in water chemistry following a major recharge event. Furthermore, sulfur isotopic composition was analyzed on four water samples to characterize the source of sulfate in the confined section of the Edwards aquifer and in ground water from the Hosston and Glen Rose Formations beneath.

AQUIFER HYDRODYNAMICS

Ground-Water Flow in the Edwards Aquifer

Regional ground-water flow patterns can be inferred from the distribution of hydraulic head in the aquifer. Two potentiometric surfaces were constructed. Figures 13 and 14 show the hydraulic-head distribution during high-flow conditions and low-flow conditions, respectively. Both potentiometric surfaces show a general west-east

Table 2. List of wells and springs sampled in this study.

Well	Name/Owner	Depth (ft)	Elevation (ft)	Water-bearing unit*
58-03-901	Solana Ranch	857	780	Kcho
58-03-907	Solana Ranch	Spring	710	Kceb
58-04-201	Tohuya Springs	Spring	680	Kceb
58-04-501	Salado Springs	Spring	570	Kceb
58-12-405	F. Schwertner	400	903	Kceb
58-18-603	Knight Springs	Spring	850	Kceb
58-19-205	Texas Water Development Board	126	800	Kceb
58-19-5X	H. Smith	~120	-	Kceb
58-19-5Y	P. Gann	~900	-	Kcho
58-19-507	City of Georgetown	180	770	Kceb
58-19-609	Berry Springs	Spring	660	Kceb
58-19-622	B. Stanton	200	707	Kceb
58-13-623	Garrett	-	688	Kceb
58-19-702	Texas Water Development Board	106	870	Kceb
58-19-704	Zachry Company	846	840	Kcgr
58-19-806	San Gabriel Springs	Spring	650	Kceb
58-19-822	-	Spring	750	Kceb
58-19-910	Texas Water Development Board	165	695	Kceb
58-20-4X	Doerfler	~300	-	Kceb
58-20-4Y	Buffalo Springs	Spring	-	Kceb
58-20-409	Texas Water Development Board	200	635	Kceb
58-20-503	E. Buchhorne	520	795	Kceb
58-20-701	C. Buchhorne	351	704	Kceb
58-21-203	City of Granger	2,606	578	Kcho
58-27-103	Texas Water Development Board	108	940	Kceb
58-27-210	City of Georgetown	165	805	Kceb
58-27-217	Texas Water Development Board	121	855	Kceb
58-27-305	Texas Water Development Board	314	840	Kceb
58-27-810	City of Round Rock	300	690	Kceb
58-27-818	City of Round Rock	285	695	Kceb
57-27-833	Texas Water Development Board	135	725	Kceb
57-27-901	F. Anderson	425	700	Kceb
57-27-902	E. C. Overall	504	685	Kceb
57-28-502	City of Hutto	787	660	Kceb
57-29-501	J. A. Bigon	1,115	618	Kceb
57-33-403	J. H. Shepler	462	770	Kcho
57-35-110	Texas Water Development Board	131	795	Kceb
57-36-402	G. Pfluger	610	755	Kceb

*Kceb: Edwards Formation
Kcho: Hosston Formation
Kcgr: Glen Rose Formation

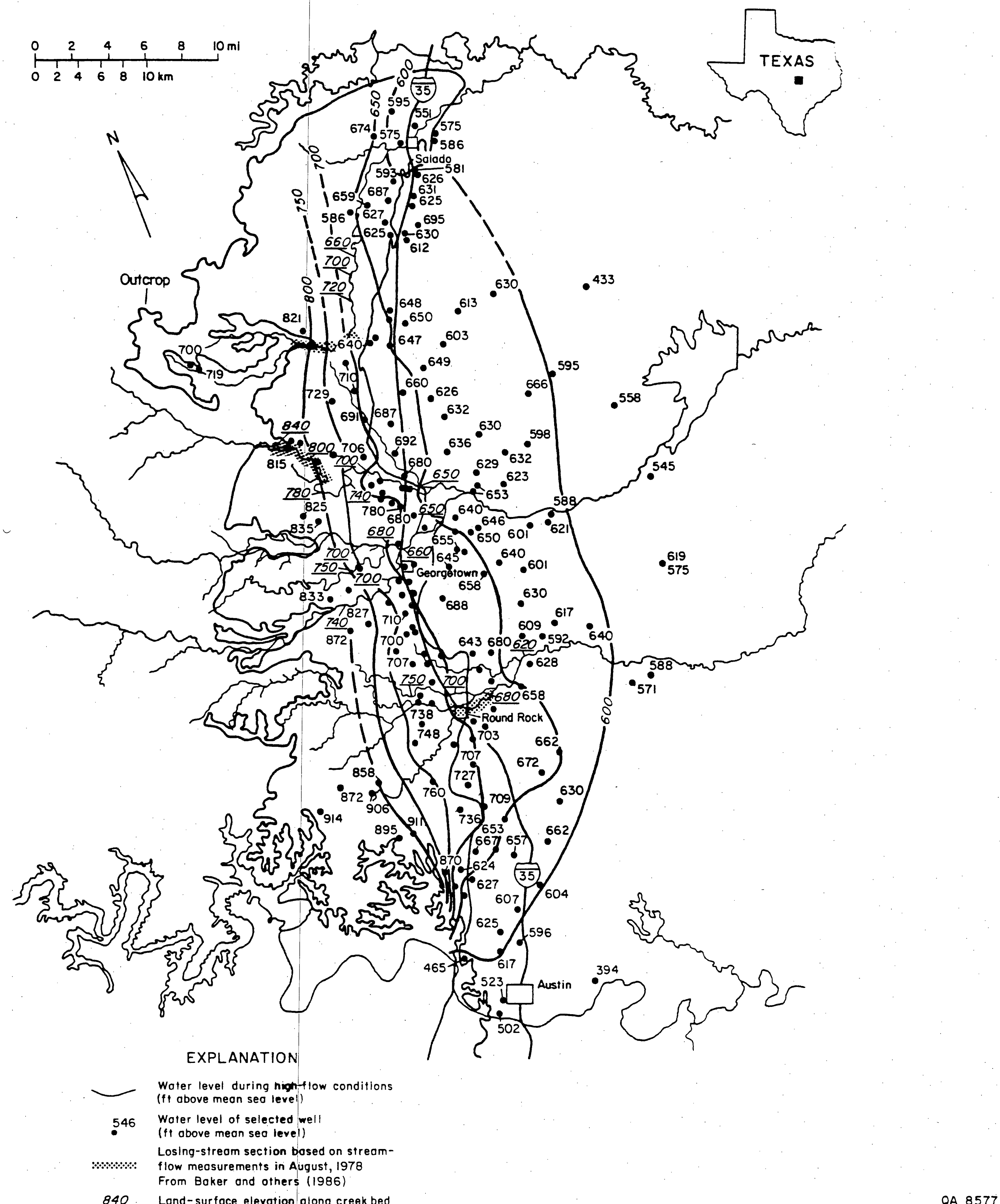

Figure 13. Potentiometric surface, representing high-flow conditions, for the northern segment of the Edwards aquifer, Austin region.

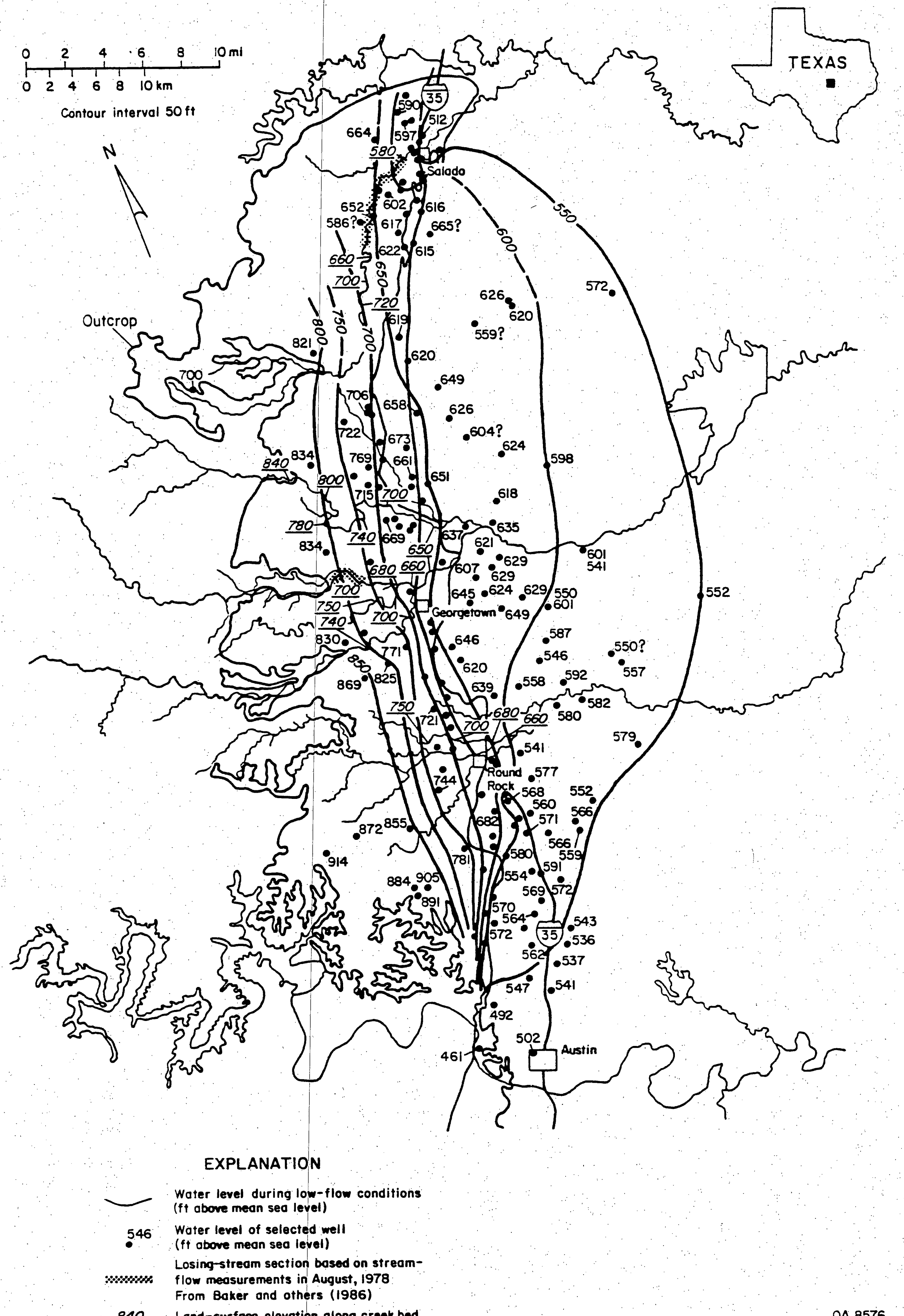

Figure 14. Potentiometric surface map, representing low-flow conditions, for the northern segment of the Edwards aquifer, Austin region.

flow pattern in the central part of the area. Toward the northern edge, ground-water flow is channelled in a northeasterly direction, parallel to the Balcones faults, toward Salado Springs (fig. 12). Similarly, extensive faulting appears to affect ground-water flow in the southern portion of the area, in Travis County. Throw along the Mount Bonnell fault is about 720 ft (220 m) near the Colorado River, displacing completely the Edwards Formation that crops out on the Jollyville Plateau to the west. Steep hydraulic gradients in the vicinity of the fault indicate that the Mount Bonnell fault acts as a hydraulic barrier, restricting ground-water flow from the Jollyville Plateau into the confined section southeast of the fault.

In the central part of the aquifer, hydraulic-head contours follow a generally north-south direction, indicating largely west-east flow. Regional ground-water flow in the central part does not appear to be significantly affected by the northeast trending Balcones Fault Zone. Faulting is less intense in the central part of the aquifer, with fault displacement generally less than 164 ft (50 m). Hydraulic gradients decrease east of the main faults, suggesting a slow flow circulation, whereas west of the main faults in the eastern part of the outcrop area, gradients are steeper, indicating faster ground-water flow circulation.

Hydraulic heads in the western part do not vary greatly over time, reflecting relatively large aquifer storativity of the unconfined section. The potentiometric surface in the eastern, confined part varies as much as 100 ft (30 m) between high-flow (fig. 13) and low-flow (fig. 14) conditions, reflecting relatively low aquifer storativity of the confined section. Within the unconfined section of the aquifer the smallest variations occur in the western part and generally increase to the east toward the confined section (fig. 6 in Slade, 1985). The cumulative effect of recharge in the outcrop combined with the general thickening of the Edwards Formation to the southeast causes a general increase in flow volume from west to east. Recharge variations will affect water levels in the eastern part of the outcrop area more than those in the western part.

Recharge and Discharge

In the Edwards outcrop area, water levels are generally less than 100 ft (30 m) below land surface. Along incised streams, hydraulic heads are near land surface. In eastern Williamson County hydraulic heads are near land surface in low-lying areas and and become generally higher than land surface along incised major streams. Flowing wells have been reported from the area.

Streamflow measurements conducted by the USGS along the main streams in the area during 1978 and 1979 show relatively few sections where stream loss occurred. The majority of the stream courses are discharge sites for ground water as indicated by streamflow increase. Stream losses that occur in the western part of the Edwards outcrop along Berry Creek and Salado Creek (fig. 12) are attributed to faults crossing the creeks (Baker and others, 1986). Similarly, a sinkhole along Brushy Creek in Round Rock that is located near a major fault acts as a recharge point for surface water during periods when aquifer water levels are below land-surface elevations. During high-flow conditions when aquifer water levels are above land surface, the sinkhole acts as a discharge site for ground water.

Sinkholes are generally found further to the west in the Edwards outcrop area on the Jollyville Plateau. These sinkholes can recharge significant amounts of accumulated surface water following heavy rainfall events. Although streams in this area act often as discharge sites for ground water, much recharge can occur in the interstream portions of the Edwards outcrop area.

Major discharge occurs through Salado and Tohuya Springs to the north and numerous smaller springs and seeps along the southern edge of the Jollyville Plateau to the south. In the central part, discrete discharge sites include San Gabriel Springs and Berry Springs (table 2; fig. 12). They occur in an area where Georgetown Formation crops out near major faults. The springs represent discharge sites of the relatively fast circulating flow system that is characterized by steep hydraulic gradients in the eastern part of the Edwards outcrop area.

The major west-east flowing creeks mostly represent discharge areas in the eastern part of the Edwards outcrop area, with numerous seeps and small springs occurring along the banks of the creeks. On a local scale, ground water is flowing toward the west-east flowing streams. Relatively short ground-water flow paths are established between the interstream areas having higher hydraulic heads and west-east flowing streams at lower elevations.

In the central part, some ground water bypasses the springs, moving farther east with much reduced hydraulic gradient. Discharge from the slow-circulating flow system presumably occurs by leakage through the confining units. Although ground-water flow circulation is much reduced in the eastern part of the aquifer, large variations are observed in the potentiometric surfaces between high-flow and low-flow conditions owing to generally lower transmissivities of the aquifer in the confined section (Slade, 1987).

Water-Level Variations

Long-Term Water-Level Fluctuations, Edwards Aquifer

The change of the potentiometric surface between high-flow and low-flow conditions in the Edwards aquifer is expressed in individual well hydrographs throughout the area. Relatively small water-level variations are observed from wells in the northern and western part of the aquifer, whereas water-level variations of as much as 100 ft (30 m) are observed in wells in the confined section (fig. 15). The hydrographs show generally synchronous variations with all water levels rising as a result of major recharge events and water levels declining during relatively dry periods, mostly during summer months.

The close correlation between precipitation and water-level variation is indicated in figure 16, which shows the hydrograph of well 58-27-305 and monthly precipitation in the area for the period between 1981 and 1986. Major rainfall events generally occur during late spring and fall and coincide with rapid water-level rises. The rate of water-level decline depends on the amount of recharge still occurring during the recession period and probably on the amount of artificial discharge of ground water through extensive pumpage. The observed water-level pattern in well 58-27-305 suggests a very dynamic hydrologic system that can be recharged and depleted relatively quickly. The rapid response indicates an aquifer system with relatively low storativity but relatively high permeability.

Lateral propagation of major recharge events through the aquifer as expressed in water-level rises in the confined section is indicated by the time lag of different hydrographs (fig. 15). Water levels in well 58-29-501 during 1984 and 1985 lag behind those in well 58-27-902, which is located further up the hydraulic gradient in this area. Water levels in well 58-29-501 continued declining in the fall of 1984, whereas water levels in well 58-27-902 were rising as a result of major rainfall events. Subsequently, water levels in well 58-29-501 started to rise; the total head change was much smaller compared with that of well 58-27-902 (fig. 15).

Comparison of the water-level elevations in figure 15 also indicates that during the drought period, water levels in well 58-27-902 dropped below those in well

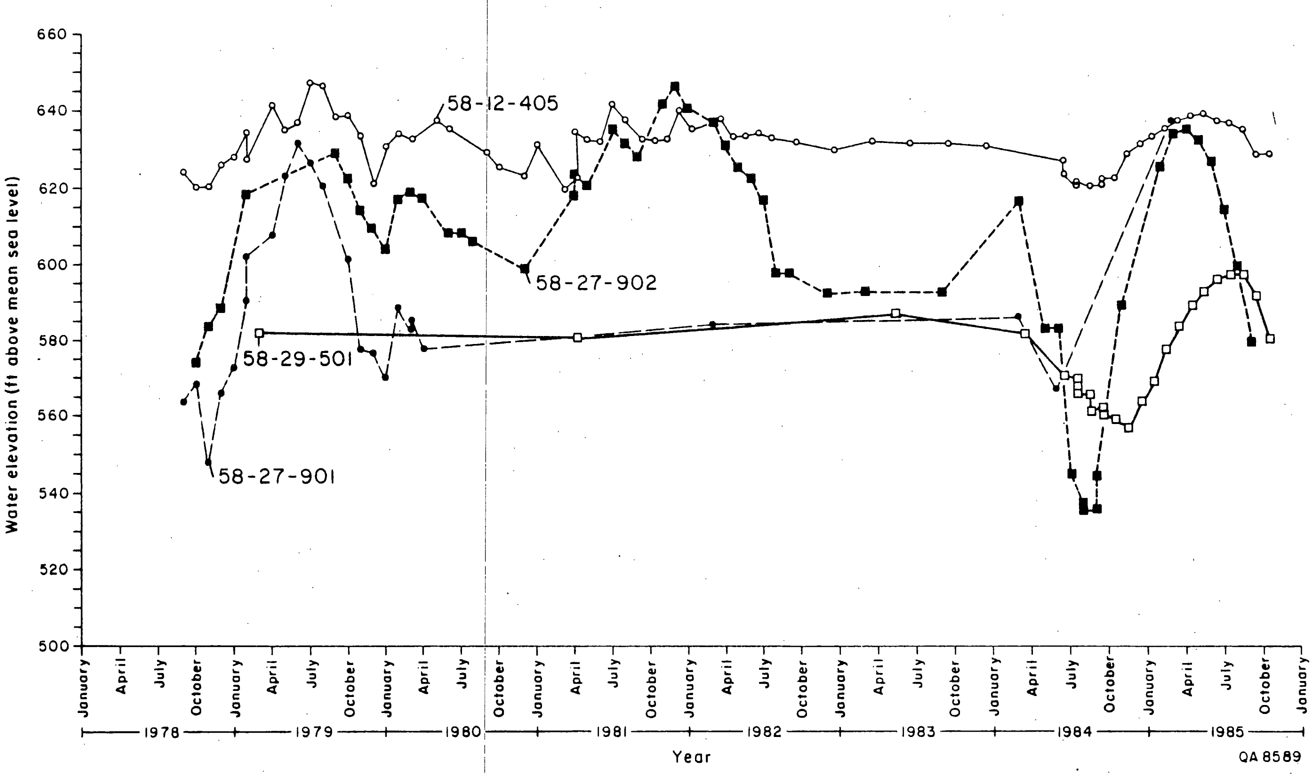

Figure 15. Water-level hydrographs of several wells in the study area: (a) well 58-12-405, (b) well 58-27-901, (c) well 58-27-902, and (d) well 58-29-501 (see fig. 12 for location).

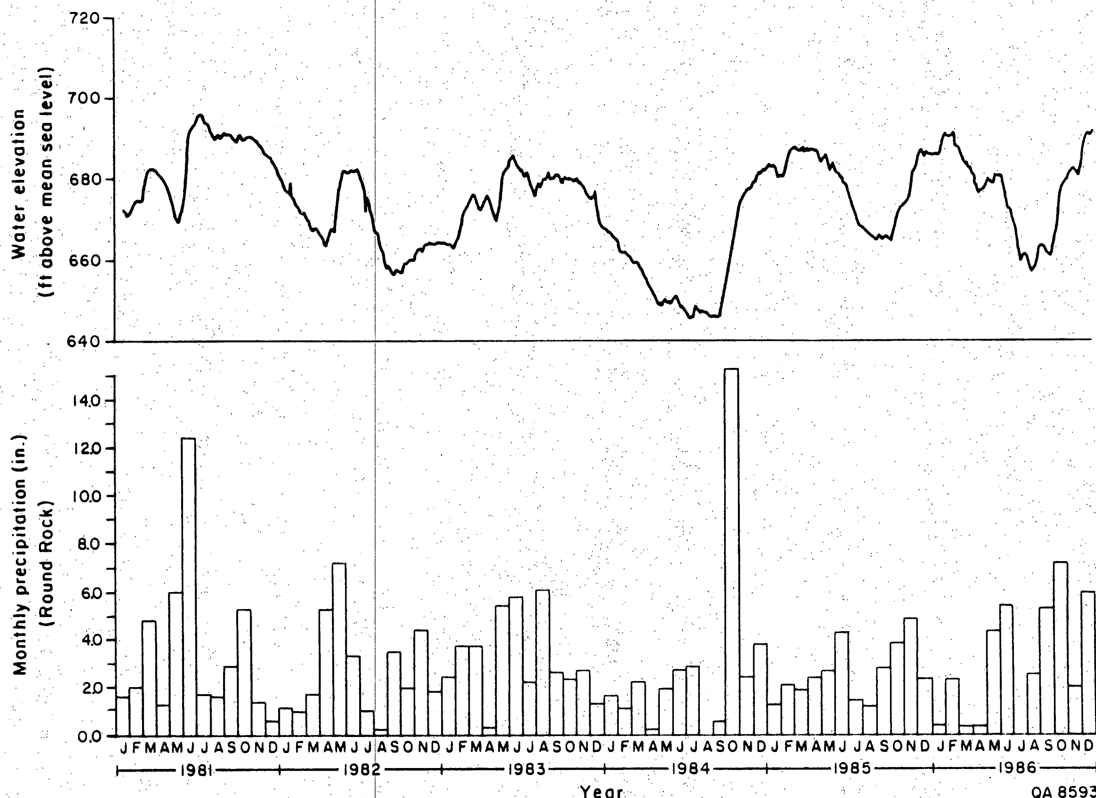

Figure 16. Water-level hydrograph from well 58-27-305 based on daily measurements (see fig. 12 for location). The bottom graph shows monthly rainfall amounts in the area.

58-29-501 located further downdip. This reversal in hydraulic heads indicates ground-water movement updip and possible influx of bad water into the fresh-water section of the aquifer during extreme hydrologic conditions.

During the 1984 drought, water levels in some wells in the area dropped below those observed during the more extreme drought in 1955 and 1956. The pervasive water-level decline during 1984 suggests that increased pumpage during the past several years significantly affected the potentiometric surface. Monthly pumpage volumes for the cities of Round Rock and Georgetown increased significantly during the last decade. Since 1983, total pumpage by the city of Round Rock exceeded that of the city of Georgetown (fig. 17). Pumpage volumes peak during generally dry summer months and decline in late spring and fall, when most rainfall occurs.

The maximum pumpage volumes during the summer months generally coincide with greatest water-level declines in well 58-27-305, located halfway between Round Rock and Georgetown (fig. 16). However, the steeper water-level declines also coincide with minimum monthly rainfall. During the recession period, discharge from the aquifer, either naturally through springs and seeps, which is gradually declining, or artificially through increased pumpage, considerably exceeds available recharge. However, no statistically significant correlation was found between monthly pumpage volumes from Georgetown and Round Rock and water-level declines in observation well 58-27-305, which suggests no drastic impacts of major municipal pumpage on water levels for large areas.

Large cones of depression that persist for more than a year have not been observed; this may be owing to lack of detailed water-level measurements. More likely, however, the amount of recharge expressed in terms of long-term average precipitation allows the Edwards aquifer to replenish itself even after a relatively dry season.

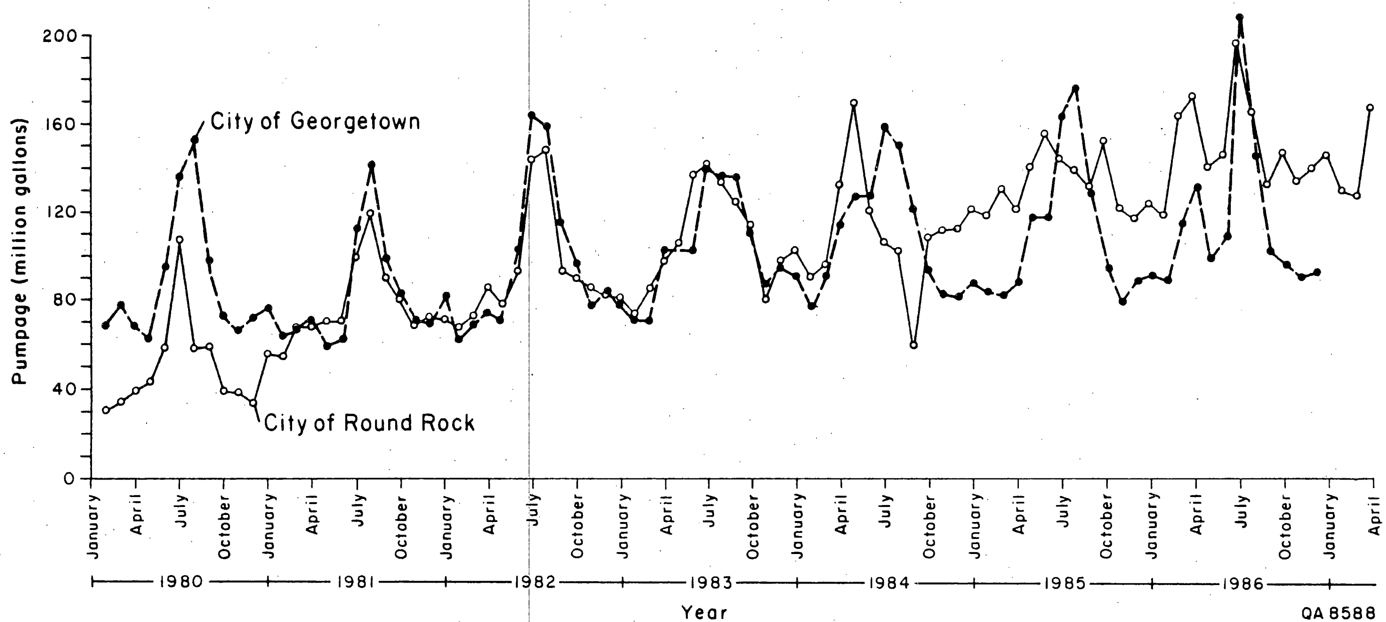

Figure 17. Monthly pumpage volumes by the cities of Round Rock and Georgetown.

Locally, however, pumpage can significantly affect water levels in nearby wells in the Edwards aquifer, as described in the following section.

Long-Term Water-Level Fluctuations, Lower Trinity Aquifer

Water levels in well 58-33-403, located in western Travis County (fig. 12) and completed in the Lower Trinity aquifer (Hosston Formation), show relatively small seasonal variations as compared with those in the Edwards well 58-36-402 located further to the east (fig. 18). More importantly, water levels have been gradually declining during the recorded period. This is true for most wells completed in the Lower Trinity aquifer. Slade (1985) compiled data from the Trinity aquifers indicating that water levels in eastern Williamson County were originally higher than water levels in the Edwards aquifer but have been declining since the 1940's.

Water-level data from Trinity well 58-29-603, located in eastern Williamson County (fig. 12), indicated a similar trend, with water levels declining steadily from about 584 ft above mean sea level in 1946 to 357 ft in October 1984. In comparison, water levels in the nearby Edwards well 58-29-501 decreased to 560 ft above mean sea level during the drought-year 1984 (fig. 15). Major cones of depression occur in the Lower Trinity aquifer as a result of pumpage around the cities of Granger and Taylor in eastern Williamson County (G. Duffin, personal communication, 1987). At present, water levels in the Lower Trinity aquifer in the eastern part of the area are significantly lower than in the overlying Edwards aquifer. The overall decline in the Trinity water levels could have a significant effect on the hydrology and hydrochemistry of the deeper parts of the Edwards aquifer, as discussed in the following section.

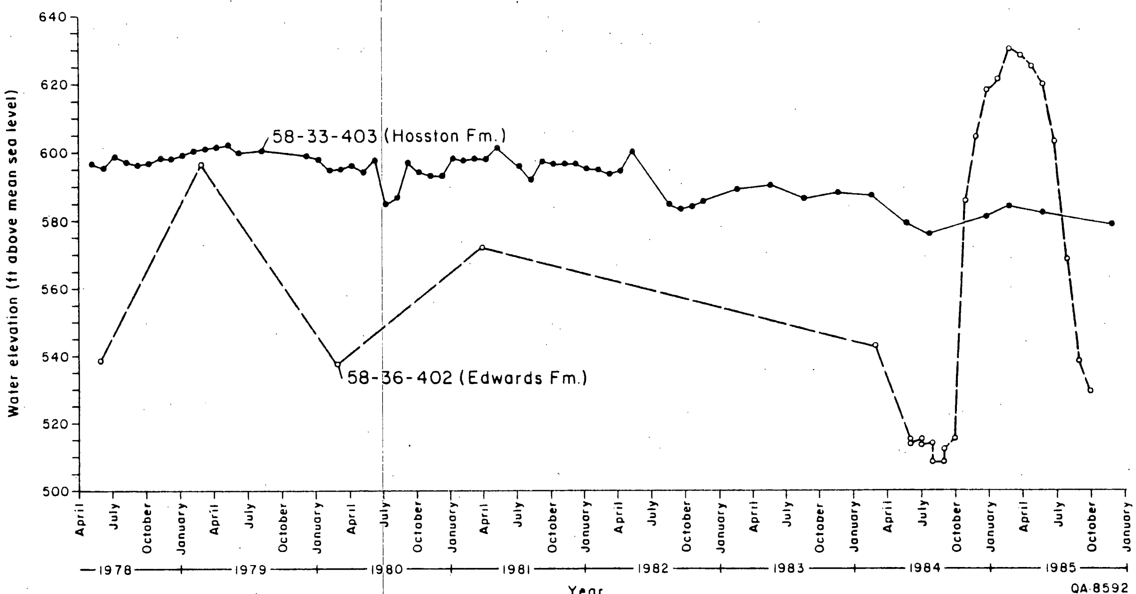

Figure 18. Water-level hydrographs from well 58-36-402 (Edwards aquifer) and well 58-33-403 (Lower Trinity aquifer).

Results from Water-Level Monitoring Network

Water-Level Patterns

The pattern of water-level variations from continuous water-level recordings can be used to identify confined or unconfined conditions of the aquifer. Water-level patterns showing fluid-pressure responses as a result of earth tides or barometric variations are indicative of confined conditions. Earth tide effects are characterized by semi-diurnal water-level variations of relatively small magnitude (less than 5 cm). Earth tides cause stress variations acting on the aquifer. For a confined aquifer, an increase in stress causes the water level to rise in a well that is open to the surface. Barometric pressures act only on the water table in the open well; any pressure changes will affect the water-table elevation in the open well. Water-level patterns associated with daily barometric pressure variations are characterized by a gradual rise in water level during the daytime because of a decline in barometric pressure caused by the heating of the atmosphere. However, a second peak may occur because of radiation of heat from the earth surface during nighttime, depending on cloud cover and humidity of the air.

In an unconfined aquifer, variations in stress or barometric pressure act uniformly on the entire water table, with no differential water-level response between the well and the adjacent water table. Thus, water-level variations in unconfined aquifers indicate changes in flow volume characterized by relatively smooth hydrographs owing to much higher storage capacity compared with a confined aquifer.

The difference in water-level response can therefore be used to distinguish between confined and unconfined parts of the aquifer. However, as discussed later in the section, the presence of semi-diurnal variations that indicate confining conditions does not necessarily imply that the aquifer is hydraulically segregated from surface water.

Some of the monitoring wells, most notably well 58-19-623 located east of Interstate Highway 35 on Georgetown outcrop, show distinct semi-diurnal fluid pressure responses (fig. 19). The particular water-level pattern in this well suggests that the Georgetown Formation acts as a confining unit to the underlying Edwards aquifer in the area of well 58-19-623. In comparison, water levels in well 58-27-210, located along IH35 south of Georgetown on Edwards outcrop, but close to the confining Georgetown Formation separated by a major fault, show only slight semi-diurnal patterns (fig. 19). The overall smooth curve suggests predominantly unconfined conditions.

Water levels in well 58-35-110, located west of Round Rock on Edwards outcrop, indicate more pronounced confining conditions (fig. 20) compared with those in well 58-27-210 (fig. 19). Well 58-19-507, located just east of Edwards outcrop under a relatively thin cover of the Georgetown Formation, indicates slight confined conditions (fig. 20). In contrast, well 58-19-205, located west of IH35 just north of the Edwards outcrop with a thicker cover of the Georgetown Formation than well 58-19-507, shows a uniform pattern indicating completely unconfined conditions (fig. 20).

The water-level pattern in wells 58-19-205 and 58-19-507 suggests that the Georgetown Formation does not necessarily act as a major confining layer in this area, or that relatively good lateral hydraulic communication exists between the well in the confined section and the water-table part of the Edwards aquifer in the outcrop area nearby. That is, stress changes associated with earth tides or barometric effects are compensated by lateral fluid-pressure propagation to the nearby unconfined part of the aquifer.

The more distinct semi-diurnal variations observed in well 58-35-110 (fig. 20), where no confining cover is apparent, are probably due to stratification within the

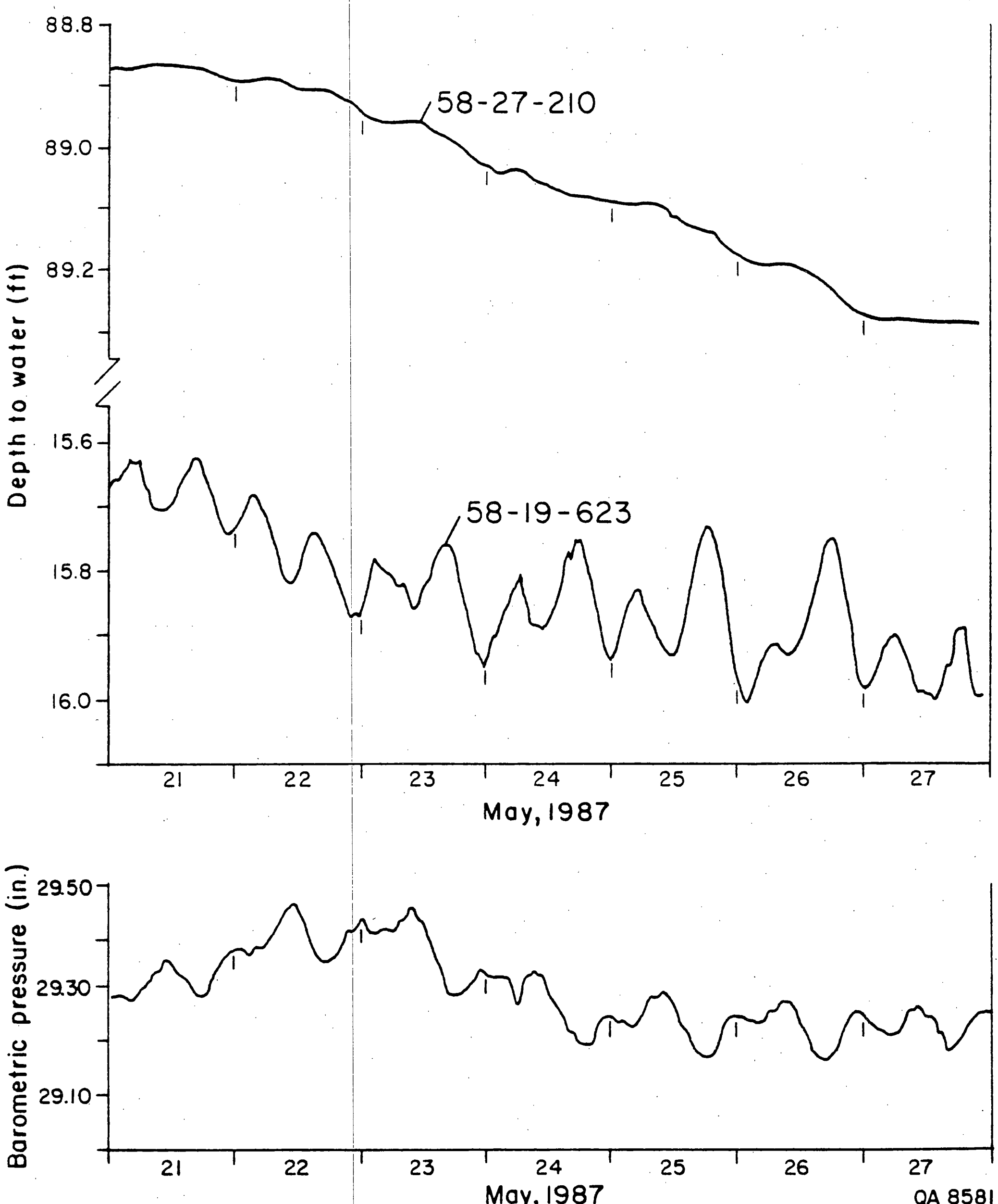

Figure 19. Pattern of continuous water-level records from wells 58-19-623 and 58-27-210 (see fig. 12 for location).

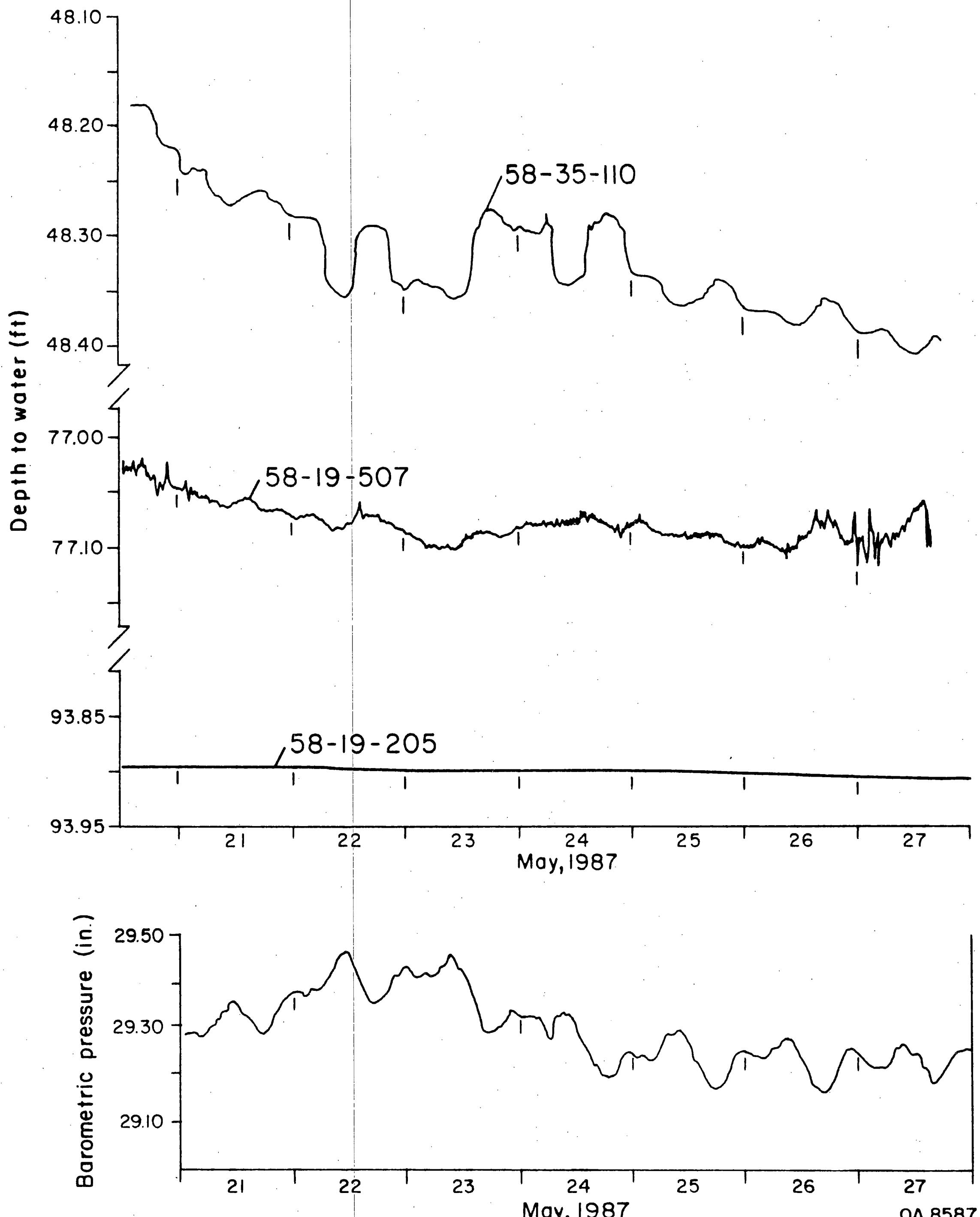

Figure 20. Pattern of continuous water-level records from wells 58-35-110, 58-19-507, and 58-19-205 (see fig. 12 for location).

Edwards aquifer. The Edwards Formation generally thickens to the south and east. Water wells in Travis County located within the bad-water zone were found to be both hydraulically and hydrochemically stratified, whereby water levels and chemical composition in the upper part of the aquifer are different from those in the lower part of the aquifer (R. Flores, personal communication, 1987).

The water-level pattern from well 58-27-305, located southeast of Georgetown and downdip from the Del Rio outcrop, as expected shows distinct semi-diurnal variations (fig. 21). The magnitudes of daily variations agree closely with those in well 58-19-623 (fig. 19). Water levels in well 58-20-409, located further east from well 58-19-623, suggest possible semi-diurnal variation (fig. 21). However, water levels do not show the cyclicity of water-level variations, suggesting that, despite the overlying Del Rio Clay, the Edwards aquifer in this particular area is not effectively confined. The lack of confining conditions could be due to hydraulic connection between the confined aquifer at the well and surface water via faults and fractures along the creek beds. Other factors that may have affected the water levels include: (1) the overall decline in water levels overwhelms possible cyclic water-level variations, or (2) mechanical problems of the recorder and float may have caused inaccurate readings (M. Dorsey, personal communication, 1987).

The variety of water-level patterns in the different wells indicates that the aquifer in parts of the Edwards outcrop area may act as an unconfined or semi-confined unit, and in areas where Georgetown Formation crops out, the Edwards aquifer can act as a typically confined system or as a typically unconfined system. However, confining conditions do not preclude the potential for rapid cross-formational flow. As described in the following section, continuous records of water level and precipitation or streamflow rates document rapid water-level responses to individual rainfall events, which suggests local recharge phenomena.

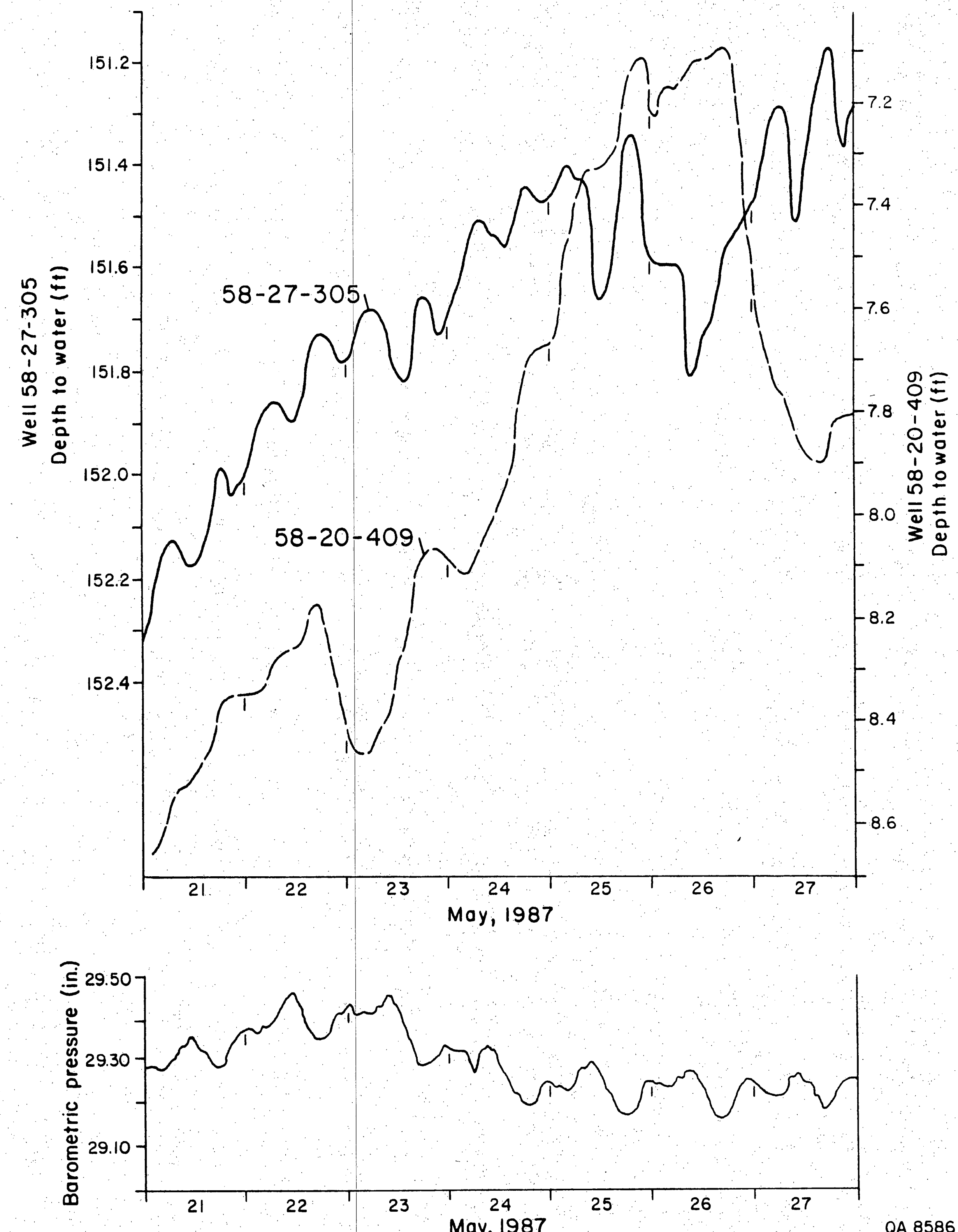

Figure 21. Pattern of continuous water-level records from well 58-27-305 (data from TWDB) and USGS Edwards well 58-20-409 (data from USGS Austin District Office). See figure 12 for location.

Continuous Water-Level Records

During this study, water levels were recorded continuously in five wells. Weekly measurements were performed in three additional wells, located in the Edwards and Georgetown outcrops west and northwest of the city of Georgetown. The hydrographs from these three wells (fig. 22) show relatively small overall variations. Water-level rises coincide with major rainfall events during that period (fig. 22). The magnitude of water-level change increases with decreasing distance of these wells from the eastern boundary of the Edwards outcrop (fig. 2). Water levels further downdip toward the eastern boundary of the Edwards outcrop show an increase in the magnitude of water-level fluctuation. This increase is due to the additive effect of recharge moving through the aquifer toward the east.

Well 58-35-110 shows greater water-level fluctuations (fig. 23) than those shown in figure 22, although it is located approximately the same distance from the confining section as well 58-27-217 (fig. 22). However, its distance from the updip boundary is much greater; thus, a much greater aquifer reservoir exists updip from well 58-35-110, and much greater volumes of ground water may pass through the immediate area of well 58-35-110.

Water levels measured weekly in well 58-19-622 (fig. 24), located along IH35 on Georgetown outcrop, exhibited water-level changes in the same magnitude as those recorded in well 58-19-623 (fig. 24), located downdip, east of IH35. Water-levels respond distinctly to individual rainfall events. The relatively large magnitude of water-level variation is in contrast to water levels in wells 58-19-507 and 58-19-205 (fig. 25), located updip from well 58-19-623, which show much smaller variations and a generally smoother hydrograph despite their proximity to well 58-19-622.

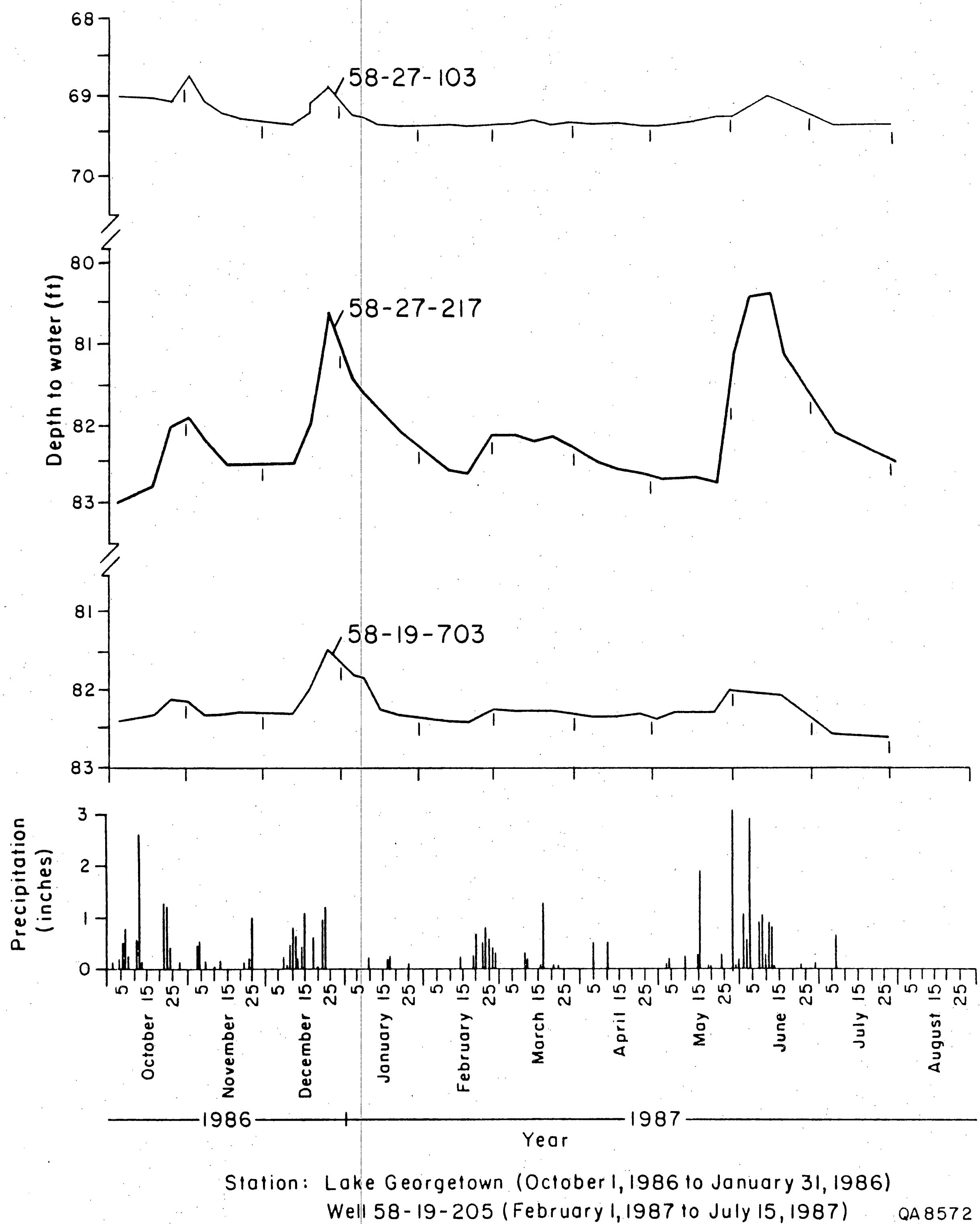

Figure 22. Water-level hydrographs based on weekly measurements for wells 58-19-703, 58-27-103, and 58-27-217 (see fig. 12 for location).

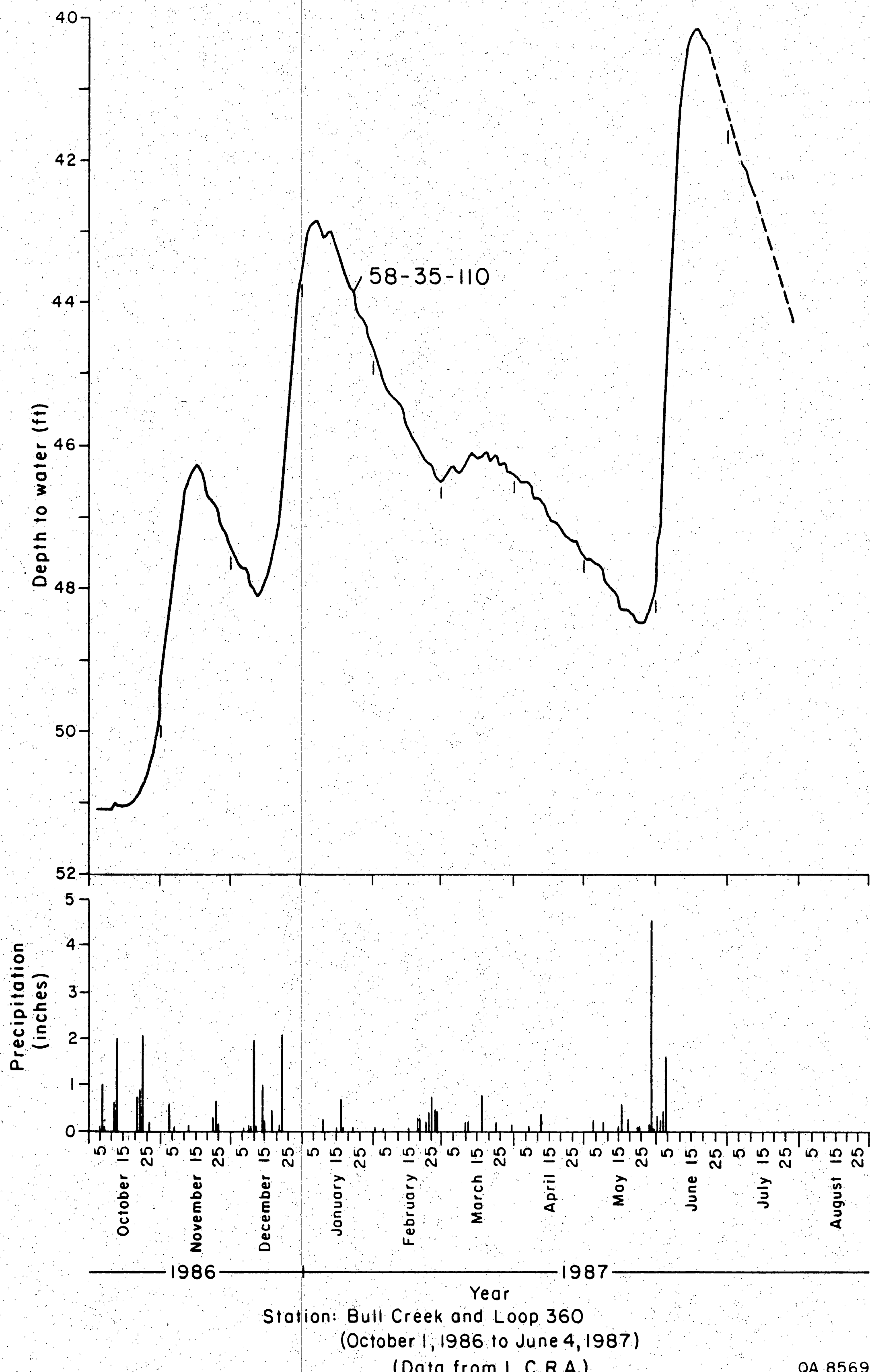

Figure 23. Daily water-level hydrographs based on continuous recordings for well 58-35-110 (see fig. 12 for location).

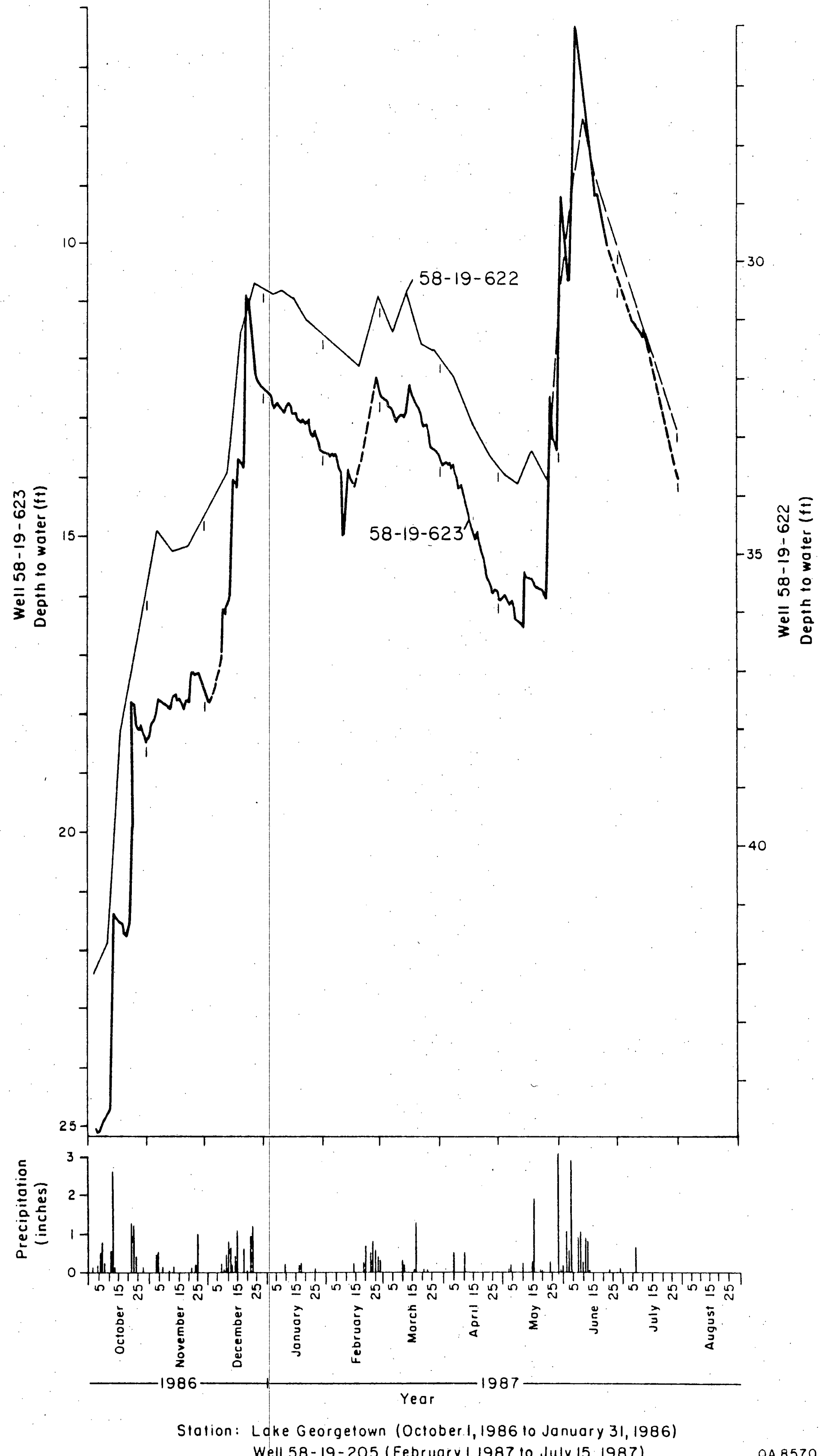

Figure 24. Daily water-level hydrographs based on continuous recordings for well 58-19-623 and on weekly measurements for well 58-19-622 (see fig. 12 for location).

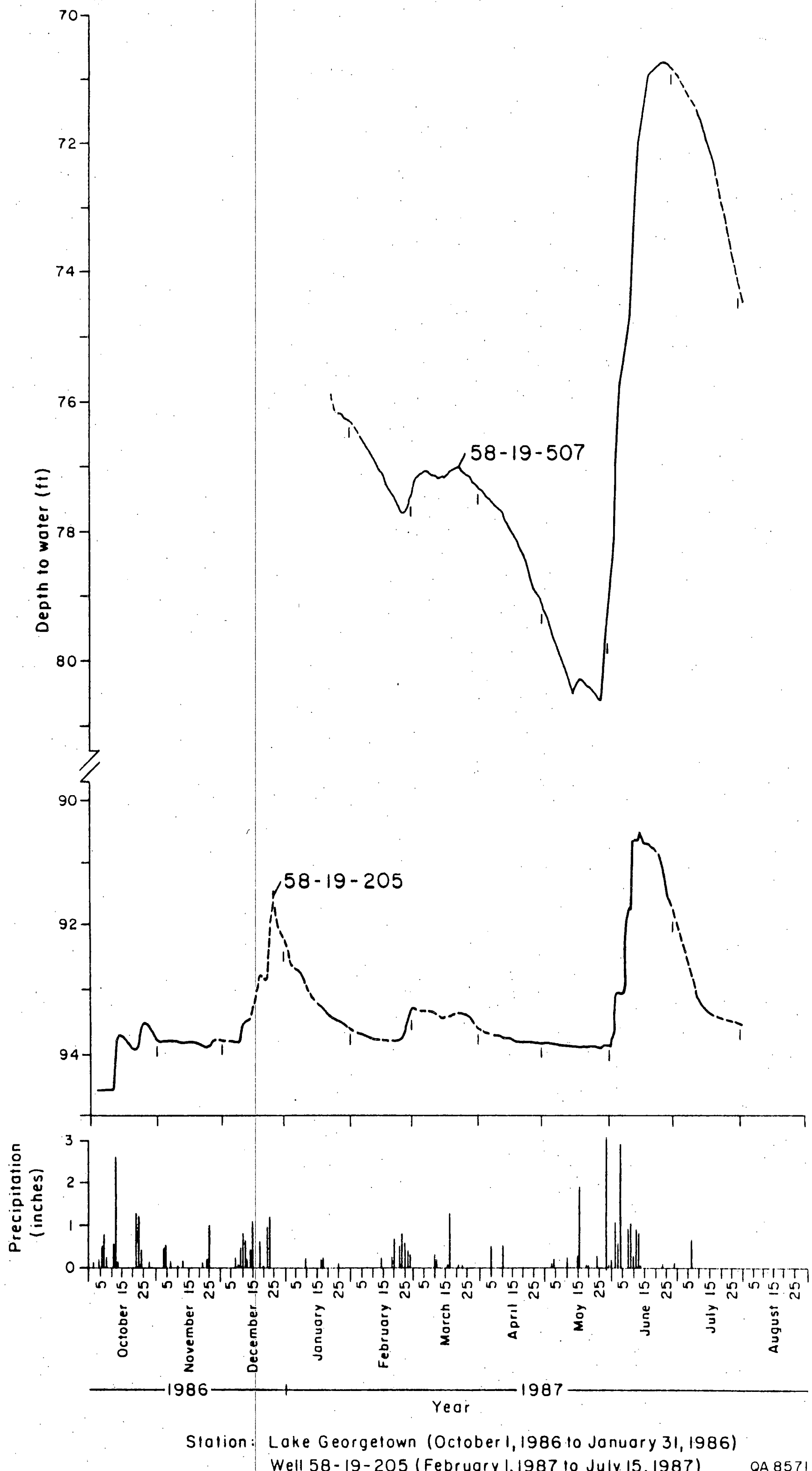

Figure 25. Daily water-level hydrographs based on continuous recordings for wells 58-19-205 and 58-19-507 (see fig. 12 for location).

Well 58-19-507 is located near a municipal pumping well for the city of Georgetown. The slope of the water-level curve (fig. 25) steepened slightly at the end of April 1987 as a result of pumpage from a well nearby, which started at that time. The impact of the pumping well nearby, which was activated periodically, was recorded on the continuous water-level charts as a sudden drop in water-levels and a more gradual recovery.

Water levels in well 58-27-210 (fig. 26) exhibit larger fluctuations than do those in well 58-19-623 (fig. 24); the latter is characterized by confined conditions with presumably lower storage capacity than an unconfined system as indicated by the daily water-level pattern in well 58-27-210 (fig. 19). The unusually steep water-level decline in well 58-27-210 may be due to drawdown from a nearby municipal pumping well. Nevertheless, major rainfall events cause rapid water-level responses of great magnitude, suggesting concentrated recharge in this particular area.

Additional continuous water-level recordings were obtained from TWDB and the USGS Austin District Office, which monitored water levels in three cluster-well sites (fig. 12). Water-level hydrographs from those cluster wells completed in the Edwards Formation and from the TWDB well 58-27-305 are shown in figures 27 and 28. Water levels in well 58-19-910 located near the San Gabriel River were affected by drawdown from a nearby pumping well showing a very irregular hydrograph pattern (fig. 27).

Water levels in well 58-20-409 (fig. 27), located east of well 58-19-623 near Berry Creek, rise more gradually than those in well 58-19-623 (fig. 24) during the period of major rainfall events at the end of May and beginning of June. Although the overall magnitudes of water-level rise in both wells are similar (note the difference in scale), water levels in well 58-20-409 show no distinct response to major individual rainfall events, and the hydrograph shows a much smoother curve. Overall, water levels in well 58-20-409 indicate a pronounced time lag between major rainfall events

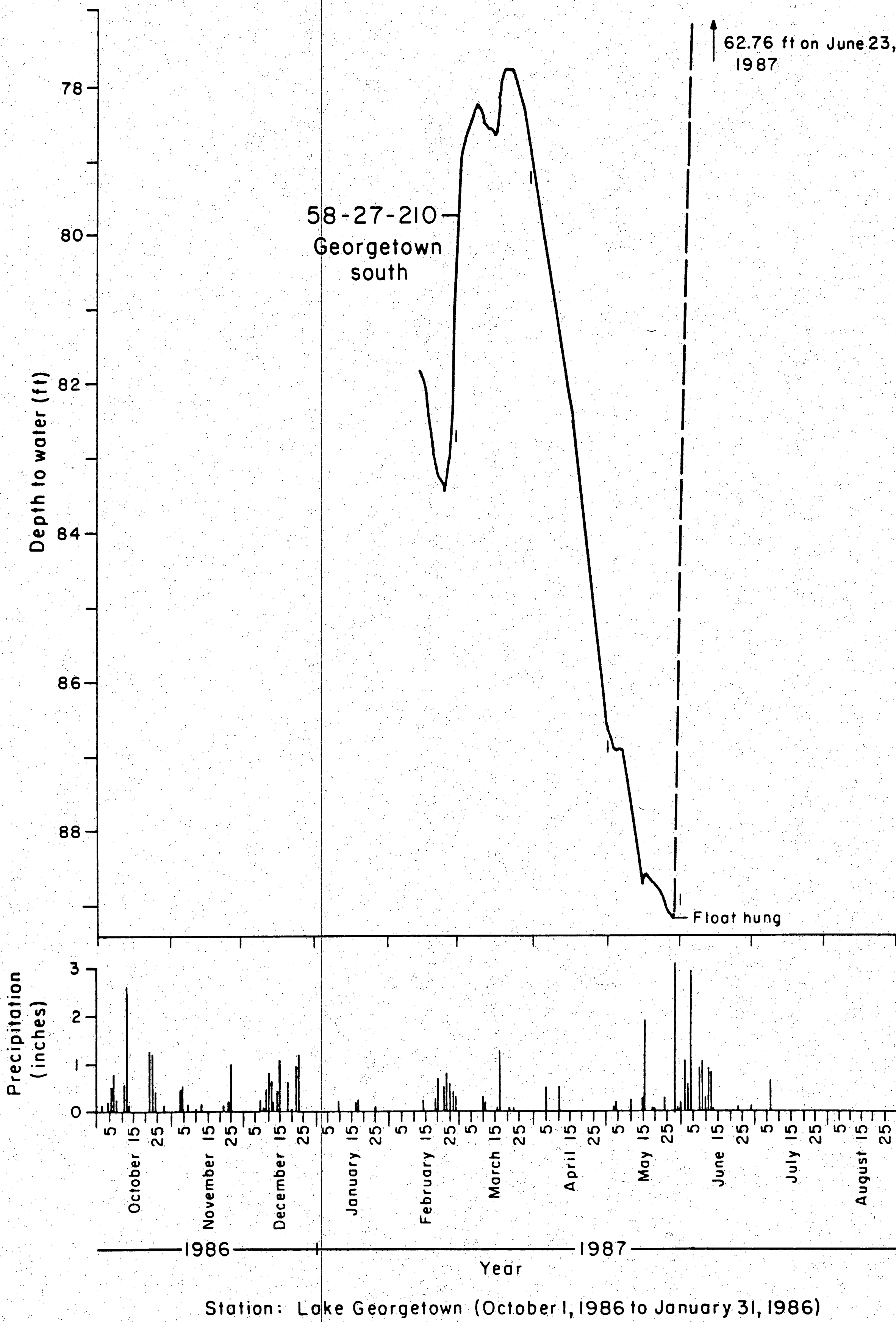

Figure 26. Daily water-level hydrograph based on continuous recordings for well 58-27-210 (see fig. 12 for location).

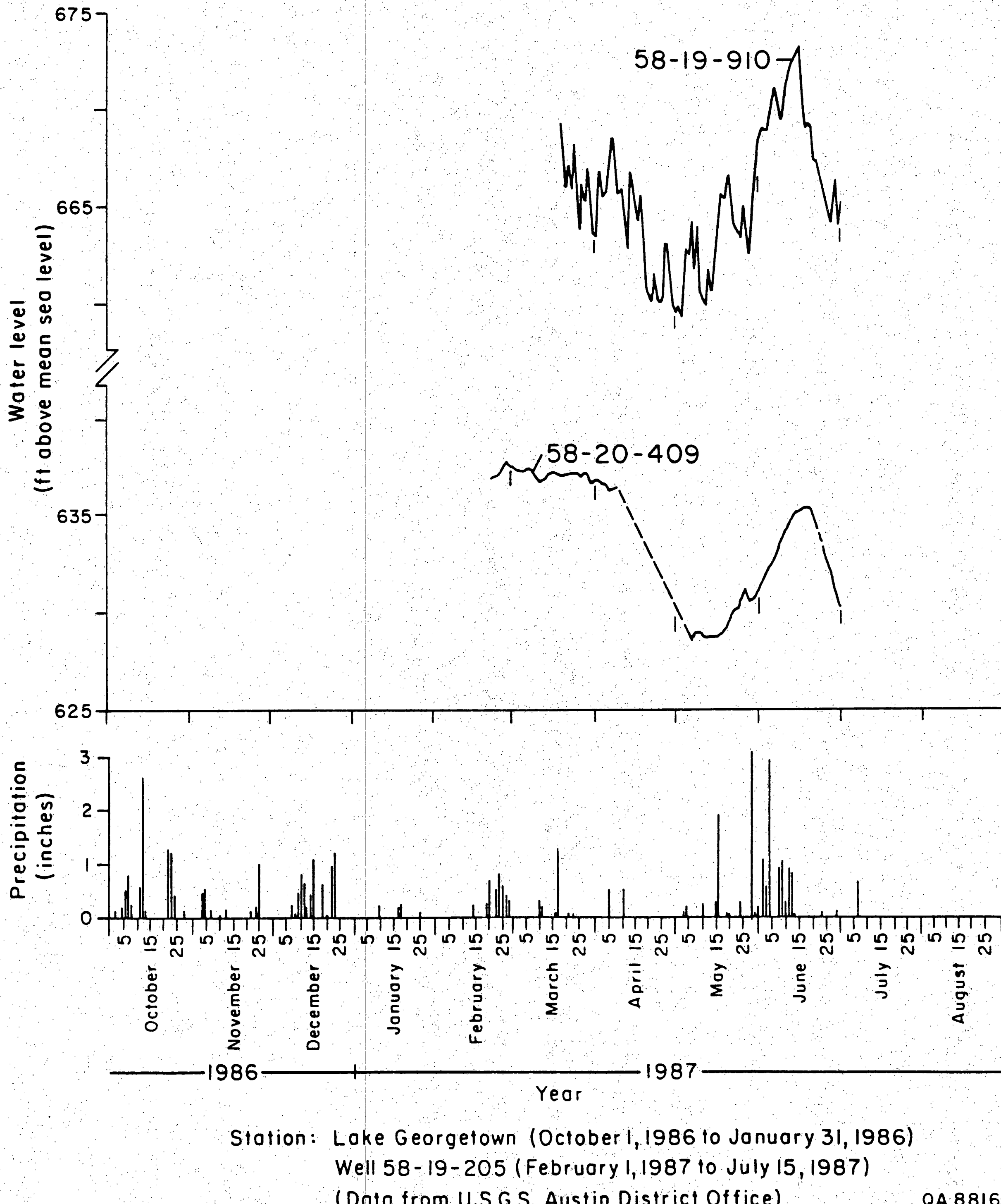

Figure 27. Daily water-level hydrographs based on continuous recordings for wells 58-19-910 and 58-20-409 (data from USGS Austin District Office).

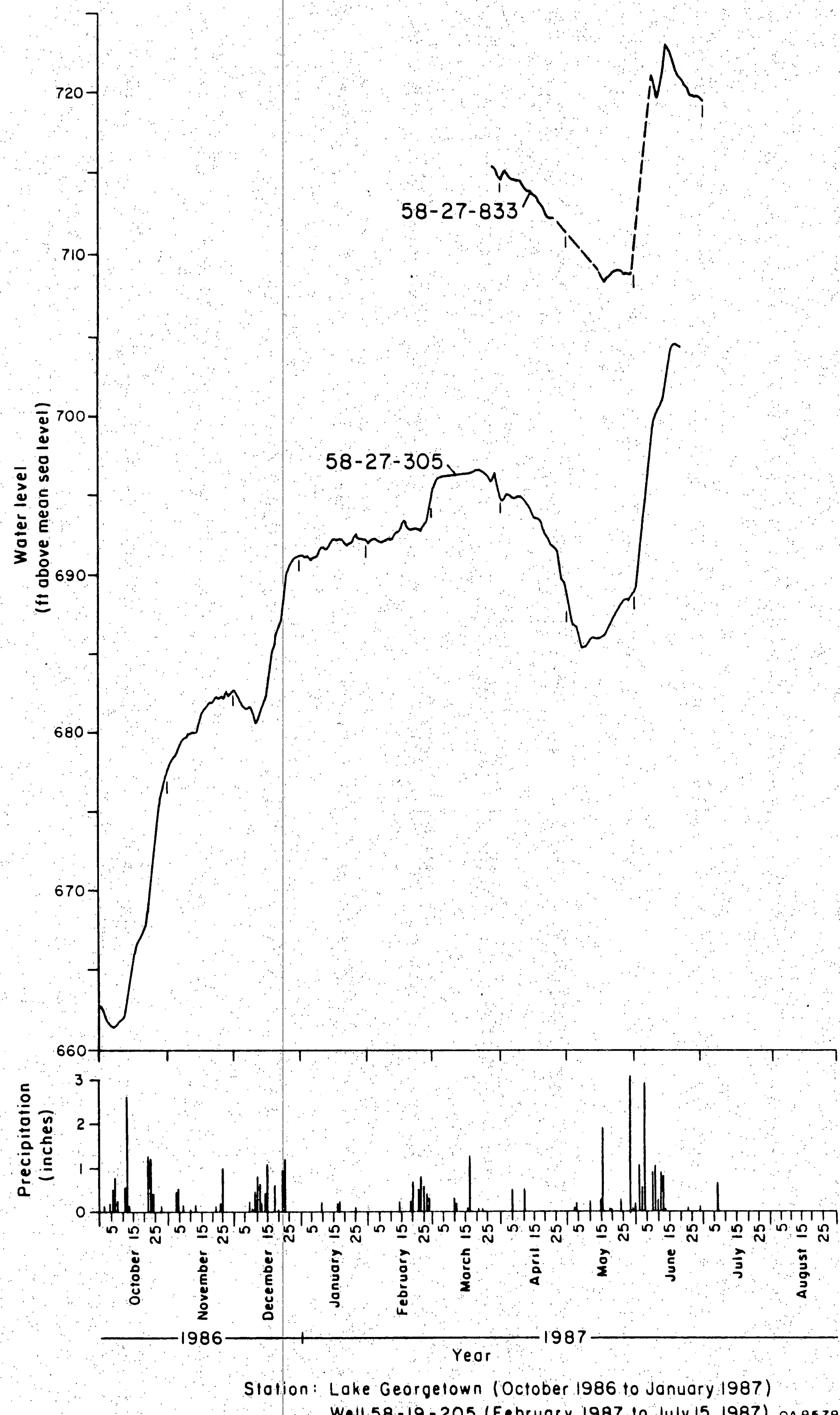

Figure 28. Daily water-level hydrographs based on continuous recordings for well 58-27-305 (data from TWDB) and well 58-27-833 (data from USGS Austin District Office).

and water-level rise in the well. Interestingly, the maximum water levels measured during the summer months in 1987 just reached the levels observed during March and April (fig. 27), whereas in most other wells water-level elevations recorded during June 1987 exceeded those recorded during March and April 1987 (figs. 22 through 28). The relatively small water-level peak in well 58-20-409 suggests diversion of additional recharge toward the discharge sites along the creeks west of well 58-20-409 (fig. 27), thereby bypassing this part of the Edwards aquifer.

Water levels in well 58-27-305, located southeast of the city of Georgetown, also indicate a more buffered and generally delayed response to individual rainfall events (fig. 28) as compared with those in well 58-19-623 (fig. 24). The water-level pattern agrees closely with that based on limited records from well 58-27-833 (fig. 28), located further updip, southwest of well 58-27-305 (fig. 12).

The described hydrographs from wells in different parts of the aquifer show a generally synchronous pattern. The variation in magnitude of water-level variations can be related to different locations within the aquifer, and to a lesser extent, to areal variation in precipitation. The different hydrographs indicate that in some of the wells, rainfall events of about 1 inch (25 mm) and more cause instant water-level responses. These extremely rapid responses are further examined in the following section.

Water-Level Response to Discrete Rainfall Events

In this section, the water-level responses to a discrete rainfall event are described in detail on the basis of continuous monitoring of water-level variations and rainfall. A short and intense rain storm on March 17, 1987, yielded a total of 1.1

inches (17.9 mm) at well 58-19-623 and 1.05 inches (26.7 mm) at well 58-19-205 over a two-hour period starting at about midnight. The hydrograph charts shown in figures 29 to 31 describe the individual water-level responses.

(1) Water levels in well 58-19-623 show an instant response starting at 4 a.m. on March 17. Depth to water decreased from 13.1 to 12.5 ft (4.0 to 3.8 m) during the same day (fig. 29). Water levels immediately started to drop again the same day after 6 p.m. and leveled off at about 12.7 ft (3.9 m) below land surface on March 19.

(2) Water levels in well 58-27-210 also reacted rapidly. However, depth to water gradually decreased from 78.7 ft (23.4 m) on March 17 to 77.8 ft (23.7 m) on March 20 (fig. 29).

(3) Water levels in well 58-19-507 started to rise at about 8 a.m. on March 17 from 77.1 ft to 77.0 ft (23.50 to 23.46 m) below land surface on March 23, after which water levels started to recede (fig. 30).

(4) Water levels in well 58-35-110 had been rising since March 4, probably responding to the previous rainfall event at the end of February. Water levels actually dropped slightly starting March 17 and reversed again on March 19 (fig. 30). Precipitation may have been restricted to the Georgetown area, and significant recharge may not have occurred in the vicinity of well 58-35-110.

(5) Water-level records for well 58-27-305 were not available prior to March 17. Depth to water gradually decreased from about 143.6 ft (43.8 m) on March 18 to 142.3 ft (43.9 m) on March 20 (fig. 31); subsequently, water levels declined again. Compared with the water-level response in well 58-27-210 (fig. 29), located farther updip from well 58-27-305, the initial response is delayed, indicating lateral propagation of the recharge pulse. The magnitude of the water-level response in well 58-27-305 is greater than in well 58-27-210, indicating the reduced storativity of the

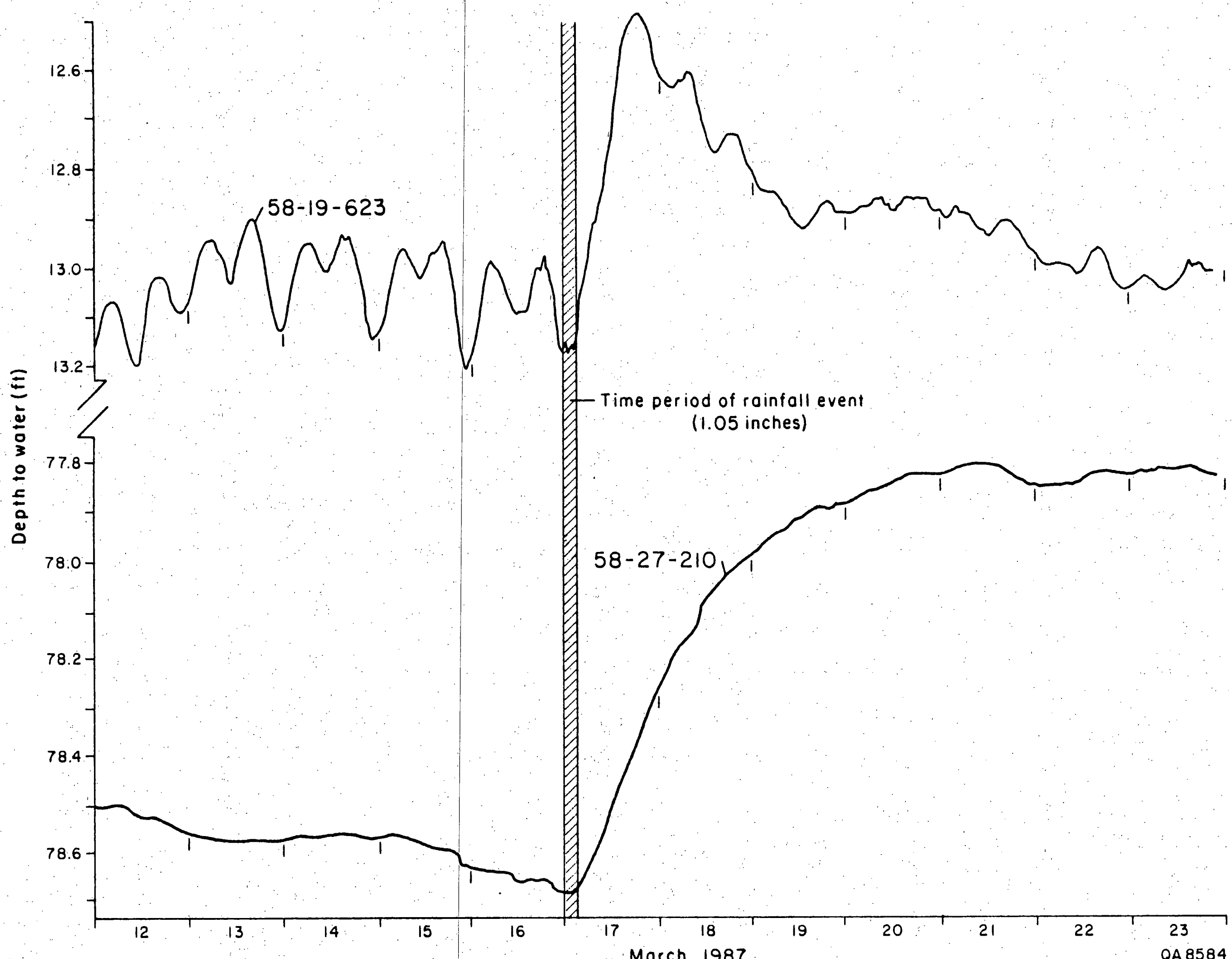

Figure 29. Continuous recordings showing water-level responses in wells 58-19-623 and 58-27-210 to a discrete rainfall event on March 17, 1987.

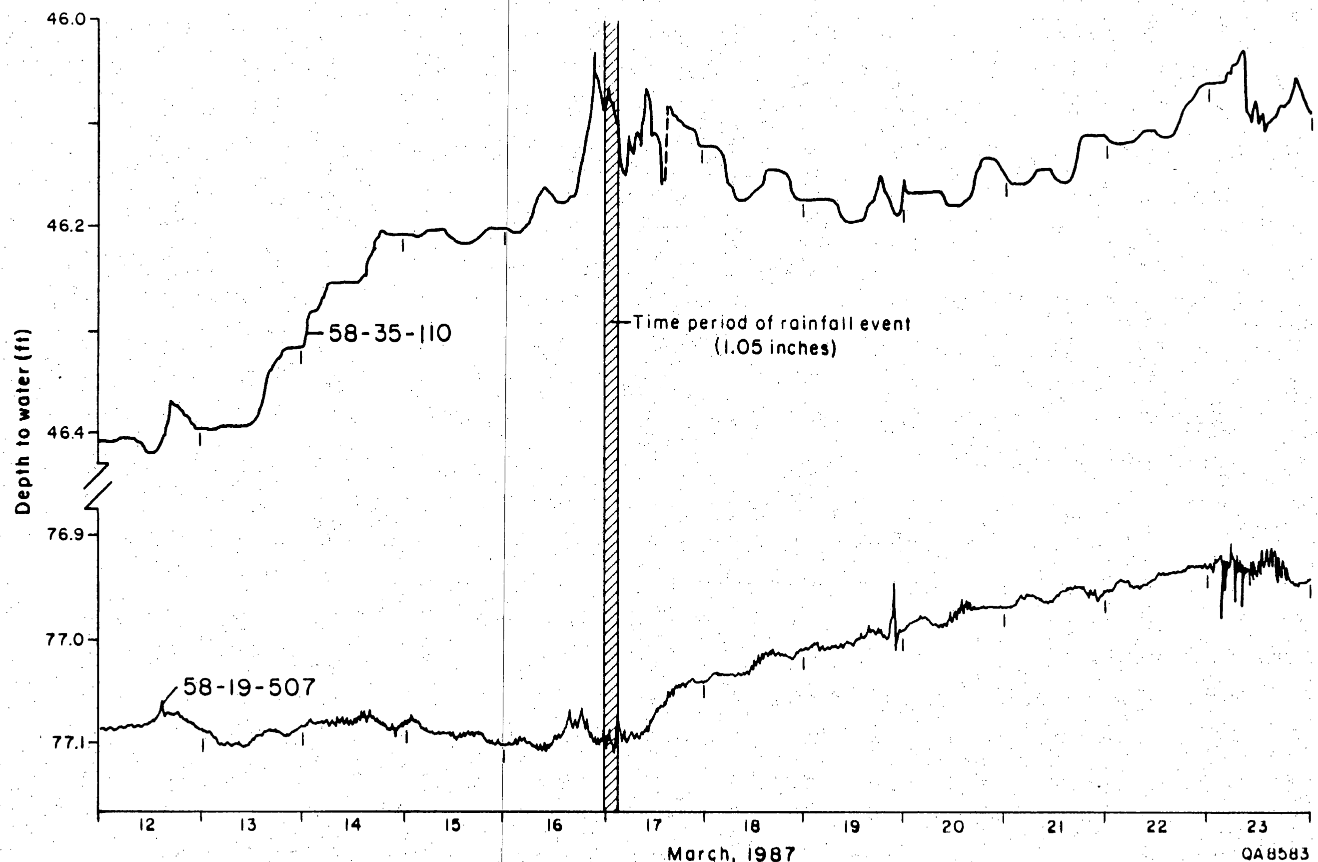

Figure 30. Continuous recordings showing water-level response in wells 58-19-507 and 58-35-110 to a discrete rainfall event on March 17, 1987.

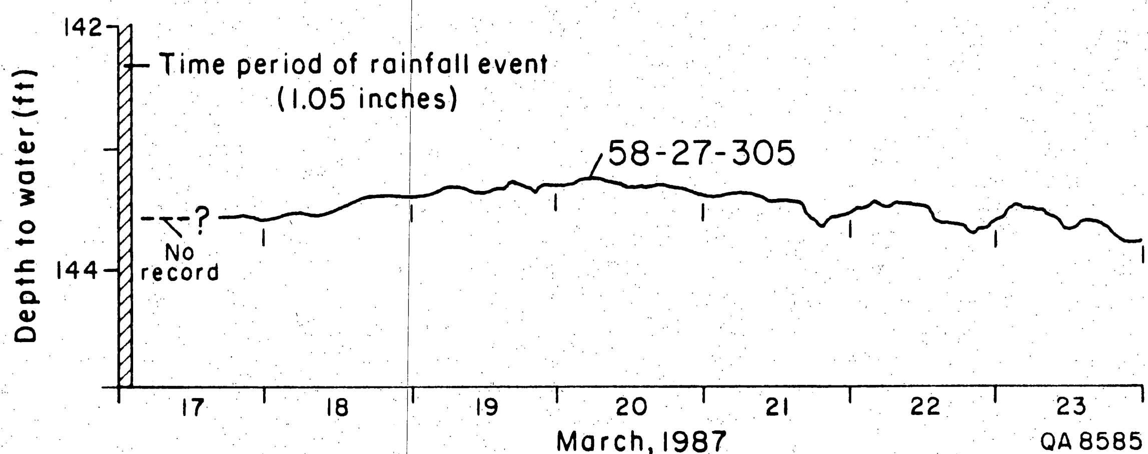

Figure 31. Continuous recordings showing water-level response in well 58-27-305 to a discrete rainfall event on March 17, 1987 (data from TWDB).

confined aquifer section (note that the scale in figure 31 is different from that in figure 19).

The initial water-level response in well 58-19-623 (fig. 29) does not lag behind the initial response in well 58-19-507 farther updip (fig. 30). Such a lag time would indicate lateral propagation of the recharge pulse through the part of the aquifer between the two wells. In fact, the water-level response in the updip well 58-19-507 indicates some lag time compared with the water-level response in well 58-19-623. Water levels in well 58-19-623 peaked within the same day and subsequently declined to an intermediate level (fig. 29), whereas water levels in wells 58-19-507 (fig. 30), 58-27-305 (fig. 31), and 58-27-210 (fig. 29) gradually rose over a period of several days. The particular water-level response in well 58-19-623 suggests localized recharge, as discussed in the following section.

Hydrologic Implications of Flow through the Georgetown Formation

The major creeks in the vicinity of Georgetown can be generally characterized as discharge sites for Edwards ground water leaking upward along faults and fractures through the overlying Georgetown Formation, which crops out along the creeks. Major discharge points are San Gabriel and Berry Springs, which are located in the vicinity of major faults along the San Gabriel River and Berry Creek, respectively.

Water levels in well 58-19-623, located on Georgetown outcrop between Berry Creek and the San Gabriel River, responded immediately to rainfall events (fig. 29). It is possible to achieve the observed rise in water level through recharge in the Edwards outcrop area updip and lateral fluid-pressure propagation from the outcrop into the confined section. Permeability would have to be extremely high and storativity extremely low along the flow path, allowing rapid propagation of fluid-pressure changes. Also, the recharge pulse had to bypass the area near well 58-19-507 (fig. 12), because the water-level response in well 58-19-507 extended over several days (fig. 30), whereas water levels in well 58-19-623 declined to an intermediate level within the same day (fig. 29). This particular response in well 58-19-623 indicates local recharge and relatively rapid dissipation of fluid pressures toward discharge points nearby. During relatively high flow conditions the hydraulic-head contours indicate a potentiometric high in the interstream area between Berry Springs to the north and San Gabriel Springs to the south (fig. 13). In comparison, water levels in well 58-19-507, further updip, show a gradual rise over several days before declining again. The rapid water-level decline to an intermediate level following a discrete rainfall event is documented by sharp peaks on the continuous hydrograph of well 58-19-623 (fig. 24) compared with the relatively smooth hydrograph of well 58-19-507 (fig. 25).

Within the timing accuracy of the recorders, the water-level hydrographs did not indicate a time lag between water-level responses in well 58-19-623 east of IH35 and wells 58-19-507 or 58-19-205 further updip. The absence of a distinct time lag in water-level responses supports a local recharge mechanism across the Georgetown Formation. Local recharge may occur through leakage along the borehole of well 58-19-623. The available well-completion information indicates that the well casing was not cemented.

On the other hand, water levels measured weekly at well 58-19-622 (fig. 24) located updip along IH35 show a synchronous pattern with approximately the same magnitude as those in well 58-19-623 (fig. 24). Information on well completion of well 58-19-622 does not indicate the possibility of wellbore leakage. Local recharge may occur through vertical flow across the Georgetown Formation, most likely along faults and fractures in the vicinity of the well. Wells 58-19-622 and 58-19-623 are located on extensions of major faults along which Edwards ground water discharges through Berry and San Gabriel Springs. Land-surface elevation at well 58-19-623 is higher than along Berry Creek to the north and the San Gabriel River to the south; thus, the interstream area represents a potential recharge zone for the two springs.

Occurrences of major discharge points, such as Berry and San Gabriel Springs, along faults and fractures through the Edwards and overlying Georgetown Formation document the flow potential across the Georgetown Formation along such faults. Geologic mapping identified fracture zones in the vicinity of major faults and related the occurrence of major springs to fault locations. T. Harriger (personal communication, 1987) reported that during the dry period of 1984, pumpage from a municipal Edwards well located near San Gabriel Springs caused springflow to cease and creek water to flow into the spring orifices, recharging the aquifer.

Streamflow measurements conducted by the USGS during 1978 and 1979 documented that the major creeks in the area are discharge sites for ground water. However, during the dry periods in 1978 and more recently in 1984, springflow at both San Gabriel and Berry Springs decreased to a trickle; increased pumpage may have contributed significantly to the drastic decline (Harriger, 1985). Consequently, the associated decline in the overall potentiometric surface in the aquifer can cause a flow reversal during extreme periods of drought and accompanied increase in ground-water withdrawal.

During the study period, water levels in the aquifer were relatively high; in fact, water levels in well 58-27-305 were at a maximum in June 1987 since the beginning of continuous records in 1981. Therefore, extreme low-flow conditions could not be monitored. The hydrograph pattern suggests that during high-flow conditions, additional recharge does not cause a comparable water-level increase to relatively low flow conditions at the beginning of October 1986 (figs. 24 and 28). During relatively high flow conditions, excess recharge is diverted directly to the major discharge site along the incised streams. The potential diversion of recharge during relatively high conditions indicates that this part of the aquifer cannot increase its ground-water capacity.

Determination of stream recharge along the rivers in the vicinity of Georgetown is difficult because only during extremely low flow conditions have recorded water levels thus far declined to levels approaching land-surface elevations in the creek beds, as shown in figure 14. A further water-level decline, either during a more extensive drought or through excessive ground-water withdrawal, is required to create a more pronounced water-table decline, which would cause a hydraulic-head reversal between the creek-bed elevation and the aquifer water table, creating a potential recharge zone in this particular area.

The Georgetown Formation can transmit ground water along faults and fractures, as documented by the presence of major springs and continuous water-level recorder data; thus, the Georgetown Formation becomes important for the delineation of potential recharge zones for the Edwards aquifer.

HYDROCHEMISTRY

Edwards Aquifer

The chemical composition of ground water in the northern segment of the Edwards aquifer, based on data from TWDB, is shown in a Piper diagram (Piper, 1944) in figure 32. In comparison, the chemical composition of ground-water samples collected during this study (table 3) is shown in figure 33. Most ground water in the Edwards aquifer is a calcium bicarbonate water with up to 50% magnesium. The composition of cations shows a distinct trend of increasing sodium with decreasing calcium and magnesium. The anion composition indicates a trend from predominantly bicarbonate to an anion mixed type water with a few samples having a predominant sulfate composition, whereas relatively more samples are characterized by predominant chloride content.

The geographic distribution of different water types in the Edwards aquifer is shown in figure 34. Calcium bicarbonate water is predominant in the outcrop areas to the west. Further downdip in the confining section of the aquifer, ground water shows a mixed bicarbonate type that changes to a sodium bicarbonate type and further downdip to a sodium mixed type water. South of Georgetown, ground water goes from a mixed bicarbonate immediately to a sodium mixed type water. The zone of mixed bicarbonate type water narrows to the south. Similarly, the zone of sodium mixed type water narrows south of Pflugerville; downdip from that zone, sodium chloride water can be found (fig. 34).

The existence of relatively narrow zones of dissimilar water can be explained by compartmentalization of the aquifer as a result of abundant faulting in Travis County. As mentioned earlier, ground-water flow in this particular area is strongly controlled by

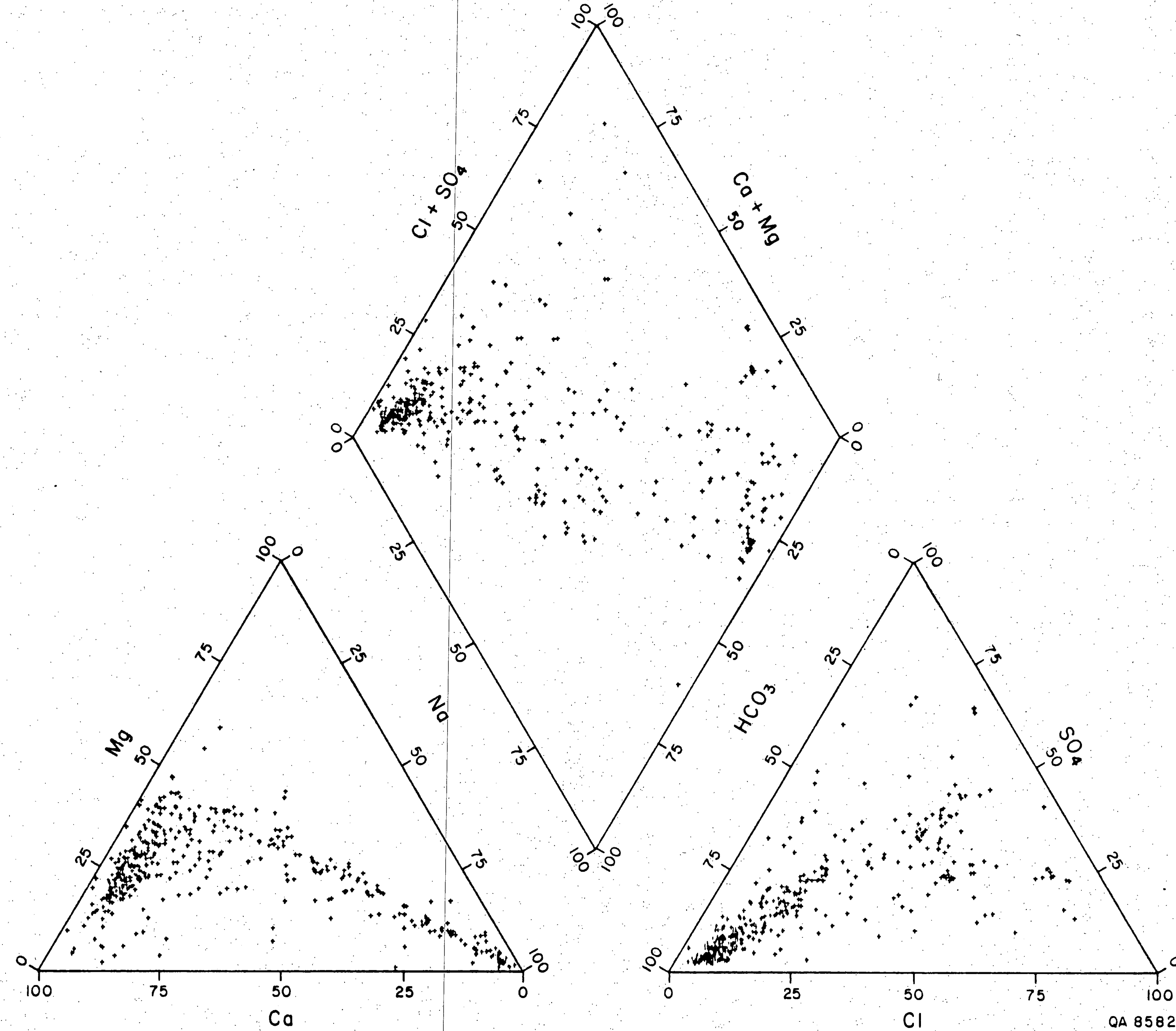

Figure 32. Piper diagram of ground water from the Edwards aquifer (data from TWDB).

Table 3. Results of chemical analyses of water samples collected during this study.

Name	Sample ID	Well	Date	Temp. (°C)	pH (field)	Alkalinity (as HCO_3)	Na (mg/L)	K (mg/L)	Mg (mg/L)	Ca (mg/L)	Sr (mg/L)	Cl (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	NO_3 (mg/L)	F (mg/L)	TDS (mg/Kg)	Tritium (TU)	pH (lab)	δ^{34} (per m
Tohuya Springs	S1	5804201	02-23-87	20.0	7.40	324	10.8	0.9	16.5	90.8	0.33	18	13.8	319	10.1	0.26	320	8.4 ± 0.4	7.49	
Salado Springs	S2	5804501	02-23-87	20.6	7.48	305	10.5	0.8	13.9	92.9	0.23	14	18.4	306	19.0	0.30	280	9.6 ± 0.5	7.74	
San Gabriel Springs	S3	5819806	02-23-87	20.9	7.35	365	10.9	0.8	18.1	103.	0.13	21	16.4	355	18.2	0.22	330	8.9 ± 0.3	7.63	
San Gabriel Springs	S7	5819806	03-04-87	20.8	7.40	353	10.4	0.7	16.7	104.	0.14	20	17.8	348	17.2	0.23	360	8.3 ± 0.4	7.28	
San Gabriel Springs	S11	5819806*	04-03-87	21.5	7.68	365	16.6	1.35	17.2	118.	0.24	24	27.0	359	36.0	0.20	436	9.5 ± 0.4	7.50	
~~Berry Springs~~	~~S4~~	~~5819609~~	~~02-23-87~~	~~21.1~~	~~7.35~~	~~348~~	~~9.43~~	~~1.6~~	~~15.5~~	~~101.~~	0.22	14	16.2	345	16.3	0.38	350	9.2 ± 0.3	7.42	
Berry Springs	S8	5819609	03-04-87	20.8	7.51	348	8.76	1.3	15.2	99.6	0.22	14	16.1	342	16.3	0.38	350	9.4 ± 0.4	7.35	
Berry Springs	S12	5819609	06-18-87	20.5	7.38	344	9.80	1.6	14.7	101.	0.20	14	14.0	336	18.0	0.40	330	9.6 ± 0.4	7.70	
Solana Ranch Springs	S5	5803907	03-03-87	18.9	7.65	405	7.92	1.9	16.5	105.	0.13	15	16.0	350	23.0	0.18	330	8.9 ± 0.3	7.52	
Buffalo Springs	S6	58204Y	03-04-87	20.6	7.45	275	12.2	3.0	3.36	132.	0.45	13	35.0	271	116.	0.44	450	11.2 ± 0.3	7.29	
	S9	5819822	03-04-87	20.8	7.45	355	17.5	0.7	21.6	95.4	0.09	33	16.8	351	17.6	0.22	380	9.8 ± 0.4	7.25	
Knight Springs	S10	5818603	03-03-87	21.1	7.70	400	39.2	0.5	19.9	105.	0.20	51	29.8	398	7.1	0.23	430	10.5 ± 0.3	7.59	
	W1	5827810	02-23-87	23.0	7.40	355	12.9	2.0	18.9	98.8	0.21	19	38.0	348	9.3	0.19	340	7.5 ± 0.3	7.42	
	W2	5827818	02-23-87	21.0	7.55	356	11.9	1.7	18.9	104.	0.16	18	34.0	355	9.2	0.27	320	7.5 ± 0.3	7.58	
	W3	58195X	02-23-87	20.8	7.10	378	10.7	0.9	22.0	103.	0.17	22	9.9	374	16.0	0.21	330	10.1 ± 0.5	7.54	
	W4	5820701	03-04-87	23.9	7.73	320	69.5	4.5	31.3	51.8	0.98	43	90.0	315	0.1	3.85	430	0.8 ± 0.2	7.70	
	W5	58204X	03-04-87	24.4	7.75	325	83.2	8.6	30.5	49.1	1.13	51	106.	319	4.5	3.64	510		7.77	
	W6	58195Y	02-25-87	10.6	7.74	435	430.	25.6	49.5	65.0	7.55	255	617.	436	4.0	2.80	1,740		7.82	
	W7	5803900	03-03-87	25.0	8.01	404	225.	14.0	10.3	15.0	7.36	111	125.	391	0.1	2.41	730		7.87	
	W8	5820503	06-17-87	23.5	7.91	350	156.	5.9	25.0	37.0	1.30	81	135.	350	0.1	4.60	620		8.00	16.3±
	W9	5828502	06-18-87	21.5	8.00	495	514.	6.1	8.1	13.6	2.10	296	390.	481	0.1	4.60	1,508		8.00	15.9±
	W10	5821203	06-17-87	39.0	7.88	470	484.	4.0	5.6	11.8	1.50	316	270.	453	0.1	3.20	1,310		8.10	11.9±
	W11	5819704	06-21-87	22.5	7.38	448	665.	45.0	98.0	119.	7.10	326	1,160.	433	0.1	5.00	2,630		7.50	21.0±

*Spring at excavation site near San Gabriel Springs.

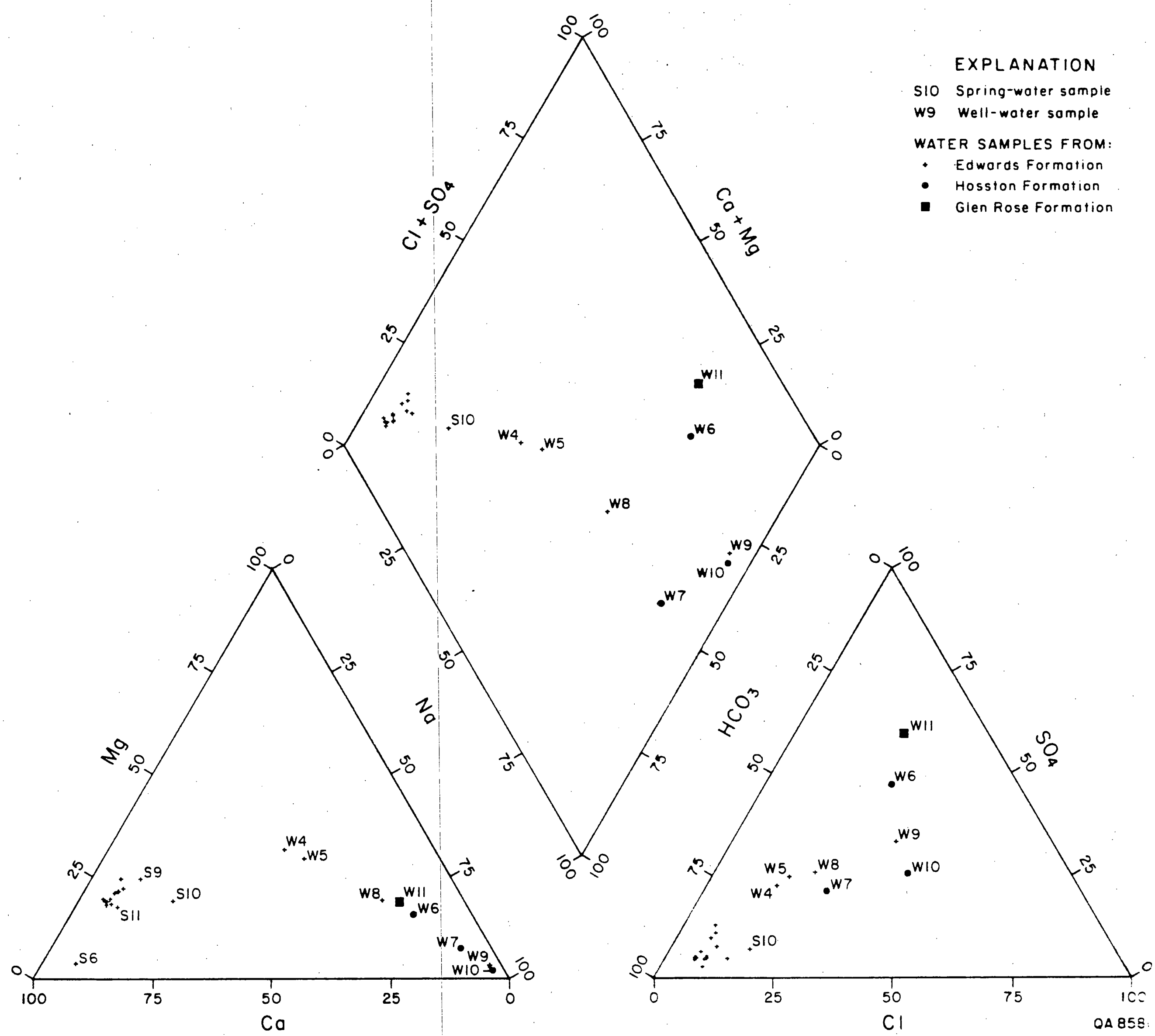

Figure 33. Piper diagram of ground water collected during this study.

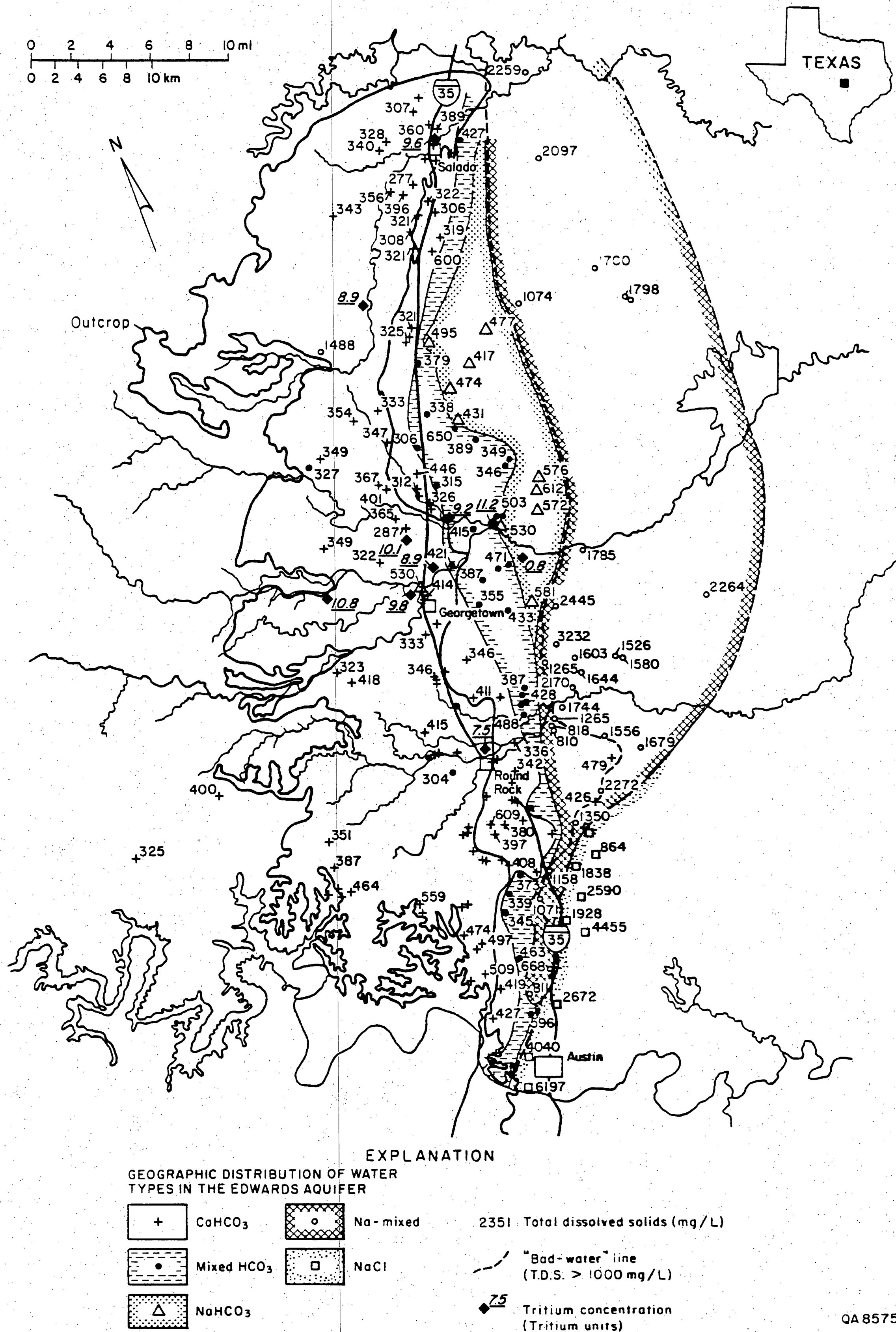

Figure 34. Geographic distribution of water types and total dissolved solids in the Edwards aquifer. Also shown are tritium concentrations in selected water samples.

faulting. Most notably, the occurrence of sodium chloride water is restricted to this area of greatest fault density, indicating deep saline waters that move upward along these faults into the Edwards aquifer. Furthermore, faults in this area prevent shallow ground water from deeper penetration.

In Williamson County, faulting becomes less extensive, with fault displacement generally less than 50 ft (15 m). Ground-water flow on a large scale does not appear to be affected by the northward-trending faults, indicating a predominantly west-east flow pattern. The zones of different water types expand laterally and follow a general trend downdip from a calcium bicarbonate water to a mixed bicarbonate, followed by a sodium bicarbonate, and finally a sodium mixed type water (fig. 34). The zone of sodium bicarbonate disappears south of Georgetown.

The pattern of ground-water types in and north of the Georgetown area reflects a more typical evolution of water recharging a sandstone aquifer and reacting with the host rock. The typical evolution of water recharging the aquifer obtains its initial calcium bicarbonate signature during infiltration through dissolution of carbonates by soil CO_2 or CO_2 from organic matter in the aquifer (Kreitler and others, 1981). The initial calcium bicarbonate water or calcium-magnesium bicarbonate water evolves to a sodium bicarbonate water as a result of cation exchange on clays. The increase in sulfate could be the result of gypsum or anhydrite dissolution (Freeze and Cherry, 1979), oxidation of pyrite, or influx of sulfides and sulfates from a downdip source; the latter was suggested for sulfate waters in the Edwards Formation in South Texas (Rightmire and others, 1979). The increase in chloride could be explained by dissolution of evaporites, presence of connate seawater, or, most plausibly, updip migration of deep-basinal brines and mixing with fresh water (Longman and Mench, 1978; Prezbindowski, 1981).

The geographic distribution of different water types reflects the extent of the two main flow systems in the aquifer. In the western part, calcium bicarbonate water is characteristic for ground water with relatively fast flow circulation. Relatively high tritium concentration (7.5 to 11.2 T.U.) in this zone indicates that ground water was recharged in recent years (fig. 34). The chemical composition of a water sample collected from an Edwards water well (58-20-701) in the confined section south of Buffalo Springs was a mixed bicarbonate water and had very low tritium concentrations of 0.8 T.U., indicating only a small amount of modern water in this part of the aquifer. Ground water in this area is considered much older than ground water further updip. The water chemistry suggests slow ground-water flow circulation, which corresponds to the zone of low hydraulic gradients east of the major springs. Note that the highest tritium concentrations of 11.2 T.U. were obtained from Buffalo Springs, located east of the calcium bicarbonate zone. Brune (1981) suggested that Edwards ground water is discharged along fractures through the overlying units. However, the water chemistry of Buffalo Springs is characterized by high calcium and low magnesium concentration (table 3), which suggests a ground water typical for the shallow water-table aquifer in the Austin Chalk that crops out in the area.

The zone of relatively slow ground-water flow circulation includes ground water with mixed bicarbonate type, sodium bicarbonate, and sodium mixed ground water. The distinction between the two different flow systems is also evident from the distribution of fluoride concentrations (fig. 35) and nitrate concentrations (fig. 36). Fluoride concentrations increase drastically east of the fast ground-water circulation system. Dissolved fluoride is generally assumed to be derived from minerals such as fluoride (CaF_2) and apatite, a common accessory mineral of igneous rocks. High fluoride concentrations in ground water from the Barton Springs segment of the

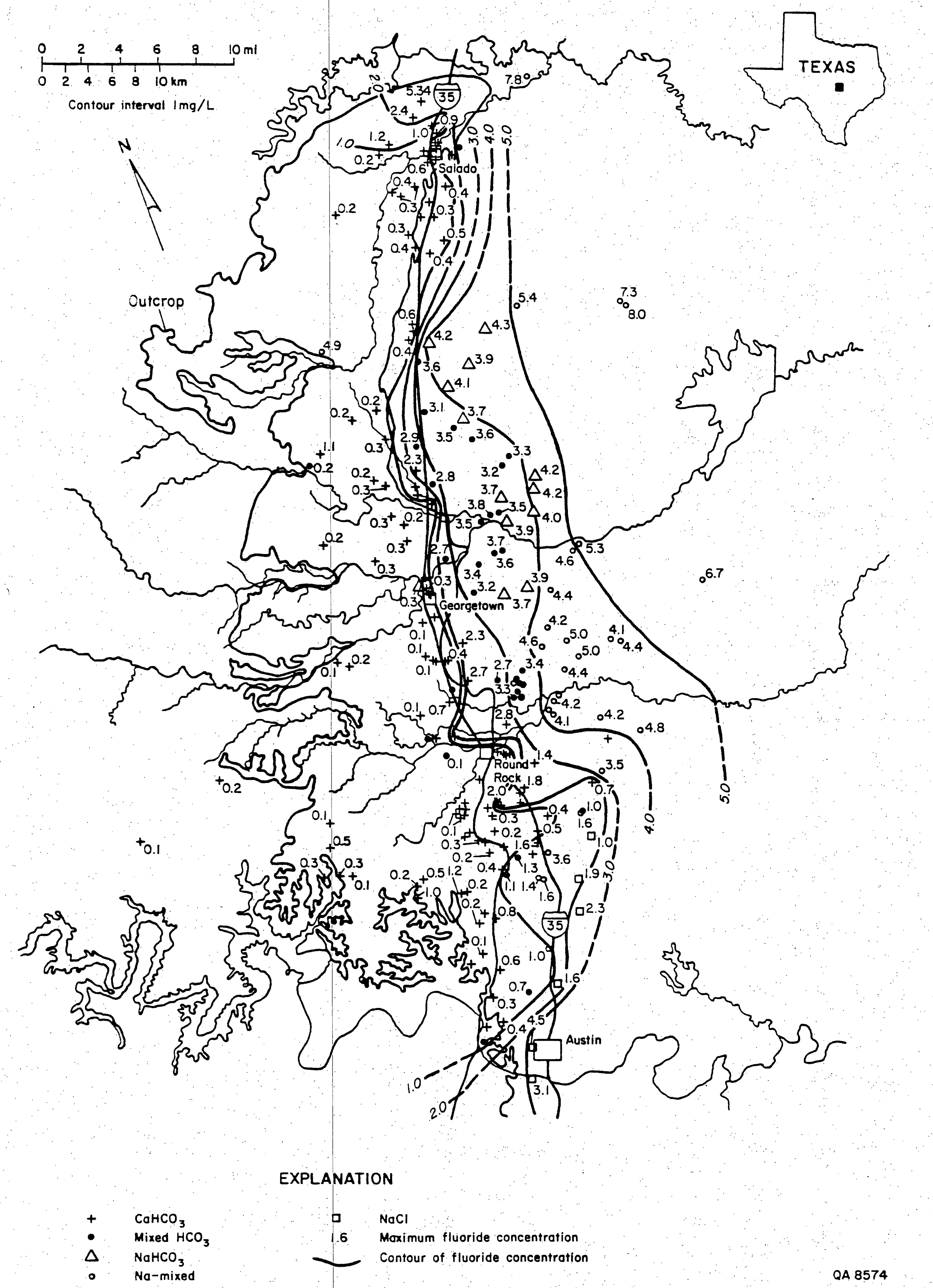

Figure 35. Geographic distribution of fluoride concentrations and water types in the Edwards aquifer.

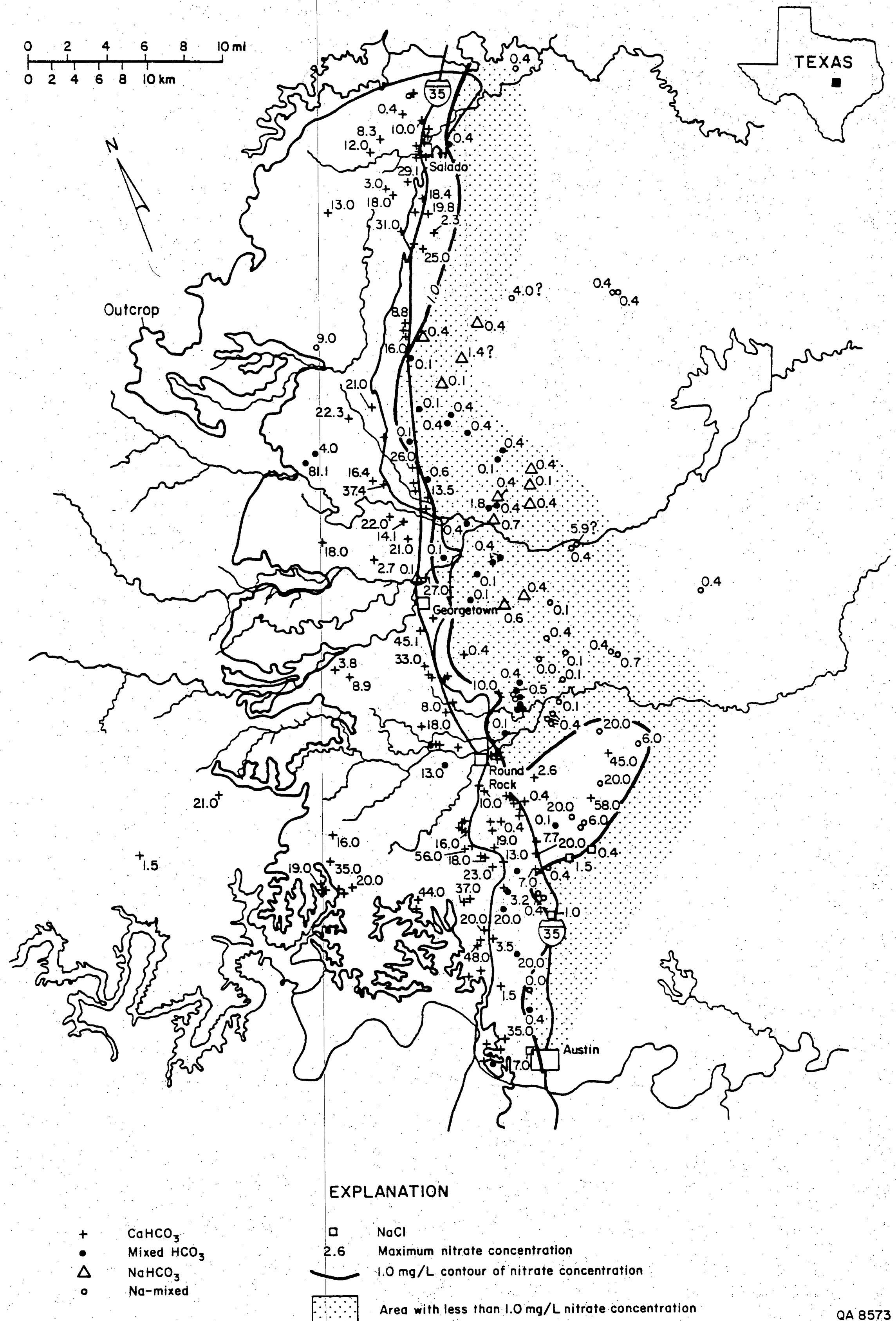

Figure 36. Geographic distribution of nitrate concentrations and water types in the Edwards aquifer.

Edwards aquifer has been related to leakage of ground water from the Glen Rose Formation (Slade and others, 1986).

Nitrate concentrations show an inverse pattern with relatively high nitrates in the western part of the area, whereas the deeper confined section is characterized by relatively low nitrate concentrations (fig. 36). Nitrate is generally an indication of surface pollution as a result of agricultural activity or local sources from sewage.

Trinity Aquifer

The water chemistry of samples from the Glen Rose Formation (Upper and Middle Trinity aquifers) in the northern segment of the Edwards aquifer (fig. 2) shows a trend of anion composition from bicarbonate to sulfate, with a few samples having an anion mixed type water (fig. 37). Cation composition shows a similar trend as the Edwards ground water except for a greater magnesium content.

The Glen Rose Formation is used as a water supply primarily in northwestern Travis County and southwestern Williamson County where potable ground water is found. Water is recharged in the outcrops to the west and presumably through the overlying Edwards Formation that crops out on the Jollyville Plateau.

The trend of increasing sodium with decreasing calcium and magnesium was not evident of Glen Rose ground water from the Barton Springs segment of the Edwards aquifer. Most analyses were from wells located in the Hill Country area, just west of the Mount Bonnell fault where the Glen Rose crops out. Only a few samples were available from the area of the Rolling Prairie within the Balcones Fault Zone. The relatively low sodium concentrations combined with high strontium and sulfate

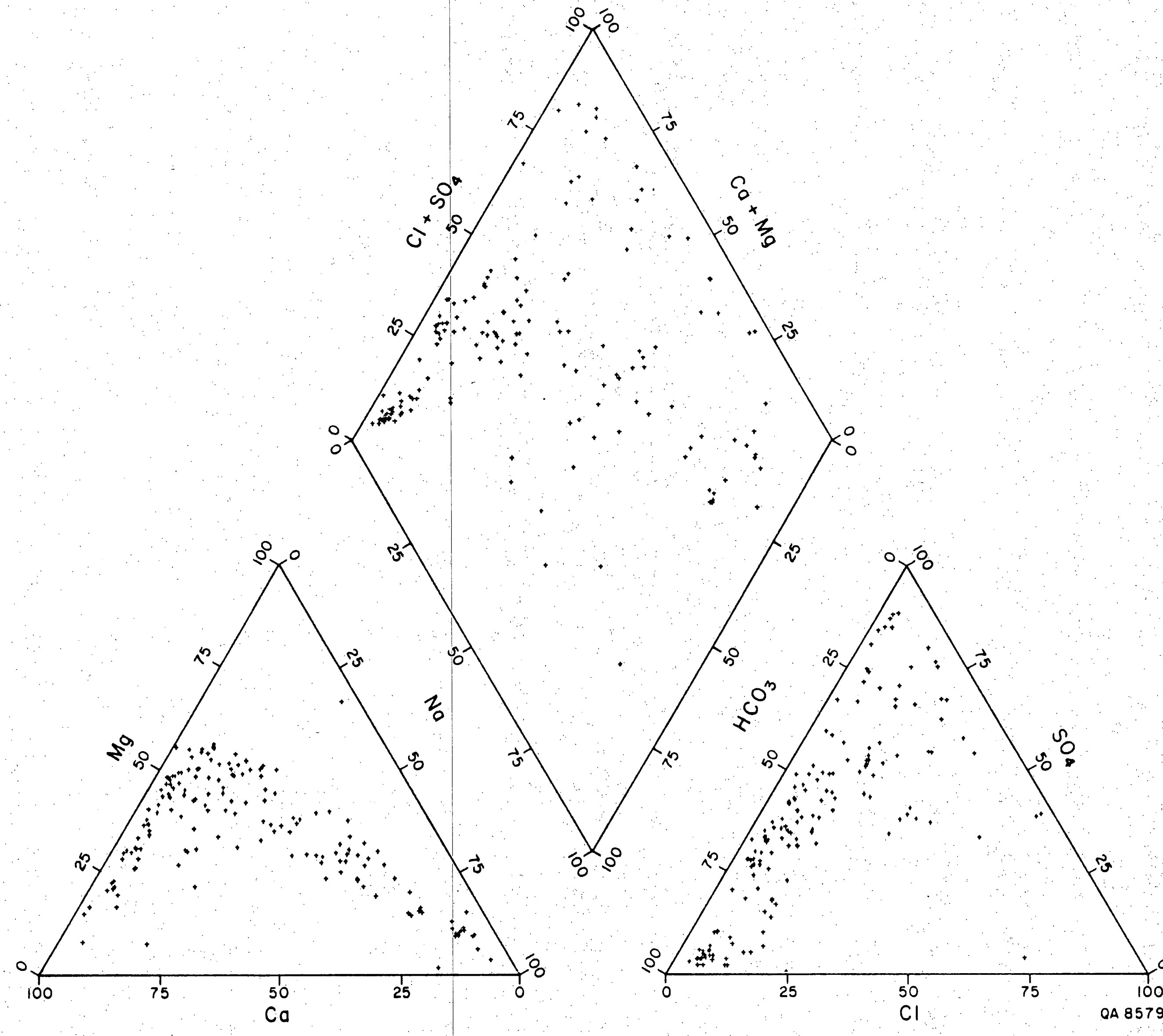

Figure 37. Piper diagram of ground water from the Glen Rose Formation (Upper and Middle Trinity aquifer).

concentrations were found to be a good indication of inflow of Glen Rose water into the Edwards aquifer (Senger and Kreitler, 1984).

Ground water from the Hosston Formation (Lower Trinity aquifer) is characterized by predominant sodium composition, again with a trend of decreasing sodium and increasing calcium and magnesium toward a calcium-magnesium composition (fig. 38). Anion composition indicates a predominant anion mixed type water with one trend toward bicarbonate, another trend toward predominantly sulfate, and a third trend toward chloride (fig. 38).

As mentioned above, water levels in the Hosston Formation have been declining more than 200 ft (60 m) over the last couple of decades from water levels that were at or higher than Edwards water levels in the eastern part of Williamson County. Water chemistry could be affected by the hydraulic changes. Ground water from the Hosston Formation in eastern Williamson County is generally less saline than the overlying Edwards aquifer and is used as municipal water supply for the cities of Granger and Taylor. The chemical composition in both the Edwards and the Hosston indicates a sodium mixed type water in this area.

Discussion

Hydrochemical Characterization

The hydrochemistry of the Edwards aquifer in the Travis County area is strongly controlled by abundant faulting and concomitant upward leakage from deep basinal waters, as suggested by relatively narrow zones of different water types. The water chemistry in the Georgetown area indicates a more evolutionary pattern of ground water, with recharge occurring in the Edwards outcrop area and subsequent reactions

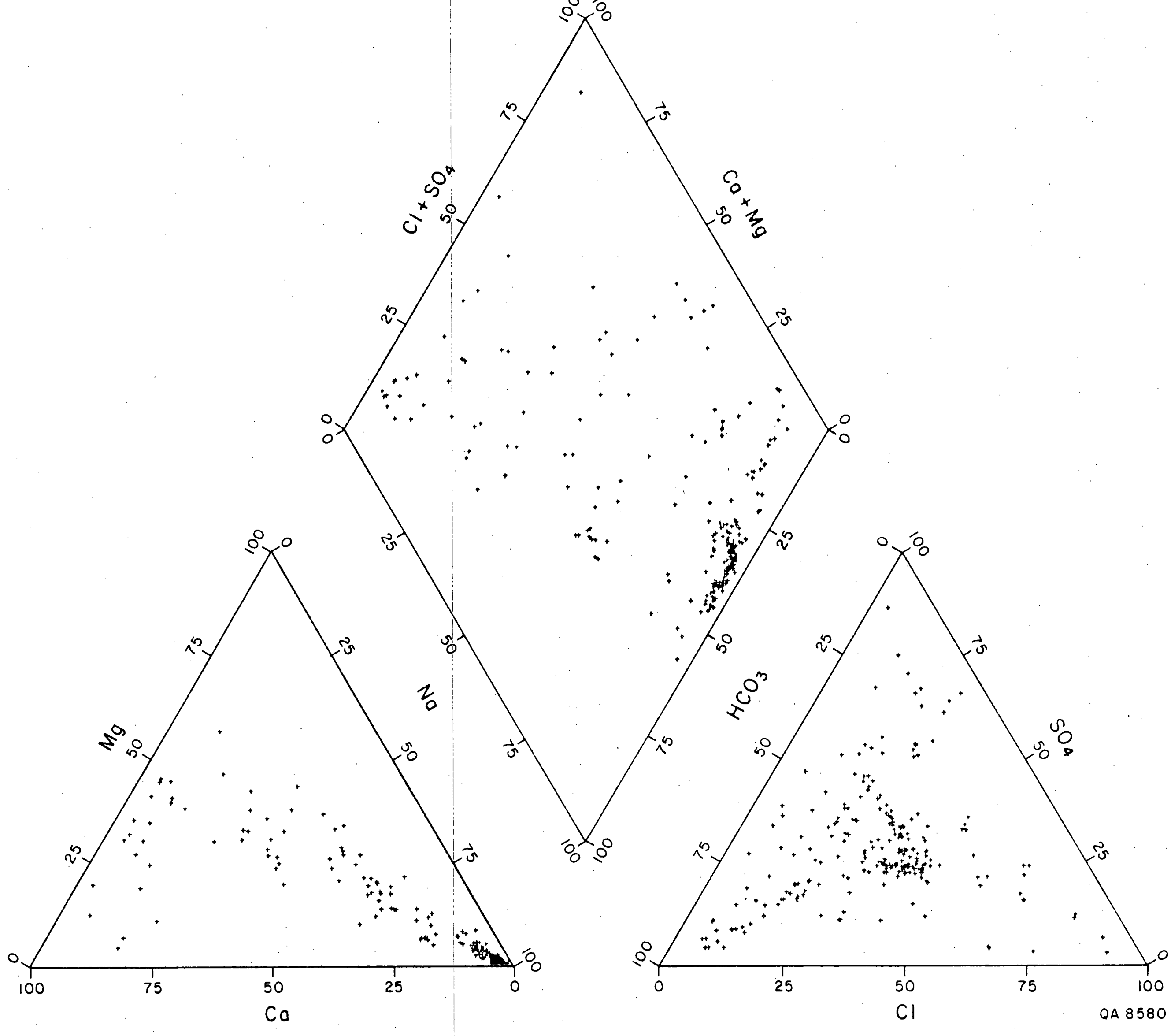

Figure 38. Piper diagram of ground water from the Hosston Formation (Lower Trinity aquifer).

with the host rock occurring as ground water moves downdip.

The increase in sodium accompanied by decrease in calcium indicates calcium-sodium cation exchange on sodium clays. As discussed by Clement and Sharp (1987), the sodium source is problematic. A possible source of clay within the aquifer is marl, which can have a highly variable clay content. However, the Edwards Formation does not contain significant marls. On the other hand, the Comanche Peak Formation below and the Georgetown Formation above the Edwards limestone are composed of interbedded nodular limestones, fossiliferous limestones, marly limestones, and marl. Ground water in the Trinity aquifers below is generally a sodium mixed water east of Georgetown, and possible mixing with Edwards water has been suggested to explain the observed water chemistry in the bad-water zone (Clement and Sharp, 1987).

The water chemistry in individual wells does not indicate considerable changes through time. As mentioned before, water levels in the Lower Trinity aquifer (Hosston Formation) have been declining for decades, causing a reversal of the originally upward flow direction from the Lower Trinity into the Edwards. However, neither the Edwards nor the Lower Trinity aquifer showed any noticeable changes in water chemistry in this area. Although both aquifers have a similar water type, water in the Edwards has higher total dissolved solids than that in the underlying Lower Trinity aquifer.

Similarly, water chemistry data collected during this study from springs in the Edwards outcrop area did not change noticeably through time, or as a result of major rainfall events. Both the major and minor chemical species as well as tritium concentration, showed only minor differences for water samples S4, S8, and S12 collected at Berry Springs before (February 22) and after (March 3 and June 18) major rainfall events (table 3).

Isotopic Characterization

Possible origin of high sulfate concentrations in the ground water can be documented from sulfur isotope analyses on four water samples from different formations. The major ionic composition of these samples (sample nos. W8 through W11 in table 3) is illustrated in figure 33. Water samples from the Edwards Formation are characterized by a Na-HCO_3-type water (well 58-20-503; sample no. W8) and a Na-mixed type water (58-28-503; W9); samples from the Hosston and Glen Rose formations indicate a Na-mixed type water (58-21-203; W10) and a Na-SO_4 type water (58-19-701; W11), respectively. Because of the limited number of samples available, the chemical results are compared with ground water samples collected from the Edwards aquifer, San Antonio region by Rightmire and others (1979) as shown in figure 39.

Ground water from the Edwards Formation sampled during this study shows somewhat depleted $\delta^{34}S$ values of about +16 $^{o}/oo$ (fig. 39b), between the $\delta^{34}S$ value for sulfide-free and sulfide-bearing waters of the southern Edwards aquifer. Sulfides were not analyzed in this study, but both water samples had a hydrogen sulfide smell, indicating low sulfide concentration and possible sulfate reduction. Although the two Edwards water samples follow the trend of increasing sulfate concentration with a slight decrease in SO^4/Cl ratios, the $\delta^{34}S$ concentration suggests gypsum dissolution as the potential sulfate source.

The $\delta^{34}S$ concentration of 21 $^{o}/oo$ for dissolved sulfate in the Glen Rose Formation indicates greater ^{34}S enrichment owing to a more reducing environment, suggested by a relatively strong H_2S smell of the water sample. Again, dissolution of gypsum appears to be the main source of dissolved sulfate.

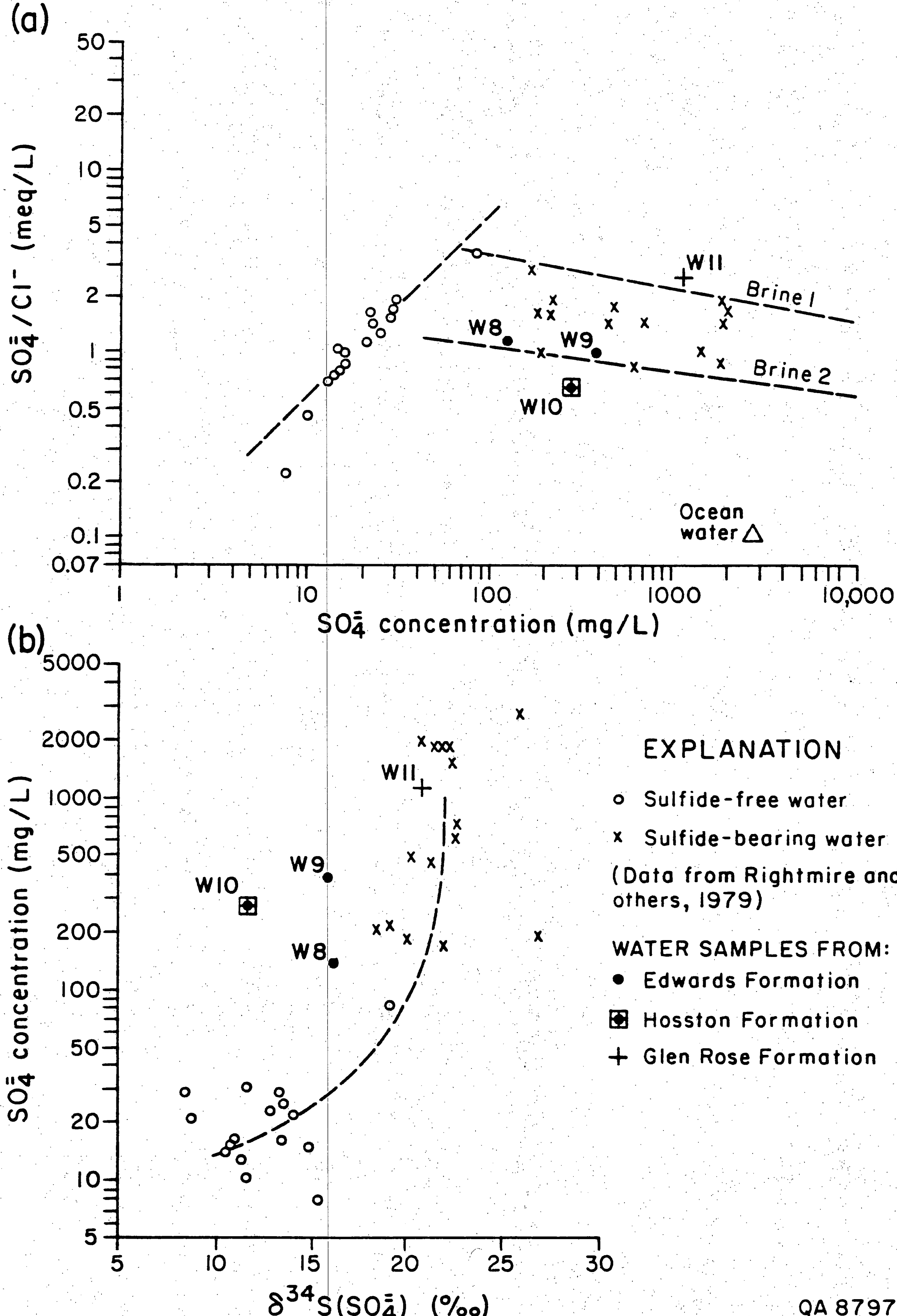

Figure 39. (a) Molal SO_4-Cl ratios versus SO_4 concentrations and (b) concentrations of SO_4 versus ^{34}S isotopic concentrations for four samples collected during this study compared with samples collected from the Edwards aquifer, San Antonio region, by Rightmire and others (1979).

Rightmire and others (1979) interpreted the data from the Edwards aquifer, San Antonio region, differently; they suggested that the sulfate originates mostly from deeper residual brines of marine origin rather than solution of sedimentary gypsum, although the relation between $\delta^{34}S$ and sulfate concentrations follows the mixing line between sulfate in shallow ground water ($\delta^{34}S$ range of +8 to 15 $^{o}/oo$) and sulfate from dissolution of gypsum, assuming a $\delta^{34}S$ of +22 $^{o}/oo$ for Cretaceous sulfate minerals (fig. 39b). They interpreted the trend of increasing sulfate concentration with a slight decrease in SO_4/Cl ratios (fig. 39a) and the presence of sulfides without significant ^{34}S enrichment of the sulfate beyond a $\delta^{34}S$ value of 22 $^{o}/oo$ as indicative of a deeper source of sulfide and sulfate. However, more recent information of the sulfur isotope age curve for sulfate minerals indicates that $\delta^{34}S$ values for Cretaceous sulfate minerals ranges between about 13 and 19 $^{o}/oo$ (Claypool and others, 1980), whereas Rightmire and others (1979) assumed a value of 22 $^{o}/oo$ (fig 39b). Thus, the $\delta^{34}S$ values of the sulfide-bearing waters in the Edwards aquifer, San Antonio region, probably indicate dissolution of gypsum ($\delta^{34}S$ of 13 to 19 $^{o}/oo$) and ^{34}S enrichment by sulfate reduction.

The isotopic composition of a ground-water sample from the Hosston Formation collected during this study indicates dissolved sulfate that is depleted in ^{34}S ($\delta^{34}S$ of 12 $^{o}/oo$) compared with sedimentary gypsum. This depletion suggests that oxidation of pyrite is a possible source of dissolved sulfate in the Hosston Formation.

Despite the limited number of samples available, the isotopic compositions show distinct differences, whereas the major ion composition does not distinguish different sources of sulfates. Although the potential for cross-formational flow and mixing of fluids from different formations cannot be excluded, the presented data suggest that the chemical composition of ground water in the Edwards aquifer is controlled by water-rock reactions along its flow path.

Hydrochemical Implications of Flow through the Georgetown Formation

The pattern of fluoride and nitrate concentrations shown in figures 35 and 36 suggests possible relationships between concentration and confining conditions in the Edwards aquifer. Both the 1 mg/L contours for fluoride and nitrate, respectively, show similar patterns in the study area. However, the concentration gradients are reversed, with high nitrate concentrations in the western part and high fluoride concentrations in the eastern part. High nitrate concentrations are generally related to shallow sources of pollution either through agricultural activities or possible impacts of sewage. Note that in areas where the Georgetown Formation crops out, elevated nitrate levels are observed. Land in the Georgetown outcrop area is being used extensively for farming, whereas the Edwards outcrop area is more typically used for ranching.

The decrease in nitrate concentrations toward the east may be a result of the aquifer dipping beneath the confining unit, the Del Rio Clay; that is, the Del Rio Clay restricts vertical leakage of potential pollutants from the surface to the Edwards aquifer. Conversely, the decline of nitrate concentration further to the east could also be related to denitrification owing to a more reducing environment further downdip as the shallow ground water transports nitrate species laterally from the Edwards outcrop area into the confined section. A third alternative is that ground water in the confined system is older and predates the addition of nitrate in the outcrop.

The origin of dissolved fluoride in the Edwards water is not understood. In the Georgetown area, the 1 mg/L fluoride contour approximtely follows the outcrop belt of the Del Rio Clay overlying the Georgetown Formation (fig. 35). The pattern of fluoride concentration may therefore indicate that the more confined section of the Edwards aquifer is defined by the overlying Del Rio Formation. The Edwards aquifer beneath the Georgetown Formation may be only semi-confined within the Balcones Fault Zone.

Southwest of Round Rock, the nitrate contour deviates to the east much beyond the Del Rio outcrop (fig. 36). Nitrate concentrations are as high as 58 mg/L, indicating shallow pollutant sources. Similarly, the concentration contours of fluoride (fig. 35) and total dissolved solids (fig. 34) deviate eastward, suggesting recharge of relatively fresh water. The general increase in faulting of the Balcones Fault Zone toward the south suggests that recharge may occur through leakage along faults and fractures through the Georgetown Formation and overlying Del Rio Clay.

RECOMMENDATIONS FOR FUTURE STUDIES

The findings of this investigation identify elements of the hydrology and geochemistry of the Edwards aquifer that require more detailed investigations. On the basis of the particular water-level responses obtained from the different wells, we recommend expansion of the network of continuous water-level recorders to cover additional areas of interest in the Edwards outcrop area and in the confined section. Recorders could be located in the vicinity of creeks and in interstream areas to investigate hydraulic behavior based on water-level responses. A systematic network within the unconfined and confined section can be used to track recharge pulses through the system and to identify the boundaries between the flow system with fast ground-water circulation in the western part and slow ground-water circulation in the eastern part. Additional monitoring wells would be needed for this type of program. Although numerous water wells already exist in the northern segment of the Edwards aquifer, most of them are producing wells and therefore could not be used for installation of continuous water-level recorders.

Future work on the hydrogeology of site-specific recharge areas of the Edwards aquifer would benefit from placement of continuous-recording monitoring wells in the area under consideration that would be completed in the Edwards Formation. Construction of monitoring wells into aquitards or the unsaturated zone is not recommended. Typically, these types of wells monitor the hydrologic properties of the porous media immediately surrounding the well. Recharge to the Edwards aquifer, however, may be along faults, fractures, and solution features. Monitoring wells that measure localized porous-media phenomena probably would not record the typical recharge event.

Comparison between precipitation and detailed water-level variations for different flow conditions can be used to identify variations in ground-water flow patterns and to assess effects of rejected recharge. The evaluation of recharge and discharge relationships based on a detailed network can be used to quantify amounts and rates of recharge in different parts of the aquifer. For this purpose additional information on hydraulic properties of the aquifer is needed. This information can be used for ground-water management purposes. Pumpage wells should be located strategically throughout the aquifer to optimize both pumpage and recharge in relation to the overall flow conditions within the aquifer.

Hydrochemical studies could focus on nitrate distributions within the aquifer to better characterize potential pollutant sources affecting the water quality of the aquifer.

Nitrate concentration patterns can be used to identify local recharge zones to the aquifer and to delineate sensitive areas for better protection. Nitrogen isotope studies ($\delta^{15}N$) can differentiate animal waste sources (cattle, septic tanks) from agricultural sources. Nitrogen isotopes could be used to test the concept that the nitrate in the recharge zone of the Edwards results from animal waste whereas the nitrates in the Edwards beneath the Georgetown Formation originate from overlying cultivation and subsequent leakage through the Georgetown Formation. Possible denitrification in the confirmed sections where nitrates are very low could also be tested.

Furthermore, a chemical sampling program could be designed to better characterize the transition between the mostly fault controlled zone in Travis County and the central part of the Edwards aquifer in Williamson County that appears to be less affected by Balcones faulting. Additional chemical constituents such as sulfides should be analyzed to test for potentially anomalous concentrations in the vicinity of faults.

SUMMARY

Geologic Conclusions

Fractures in Comanche Peak, Edwards, and Georgetown limestones that contain the Edwards aquifer may influence the capability of these strata to transmit and hold fluids. Two types of fractures that cut these strata are (1) minor faults having displacements of less than 2 m and (2) joints. These fractures are generally most abundant near major faults and flexures, although joints in Edwards limestones exist regionally. Most of the minor faults strike 340°-040° subparallel to the major faults, but some strike 250°-300°, suggesting that westward-striking cross faults or flexures may occur in the area. Minor faults dip an average of 55°. Most joints strike either 260°-300° or 340°-020°. The joint and minor fault sets have similar strikes. Many minor faults are at least partly filled with calcite; joints do not have mineral fillings. Joints of the two regional sets show no preferred abutting relationships. These observations indicate minor faults formed before the joints and that joints of the two regional sets formed contemporaneously. The minor faults are tectonic fractures. Joints may be either younger tectonic fractures or unloading fractures.

Several fracture characteristics described in this report are important to ground-water flow. Apertures of fractures in Edwards limestones can be several centimeters wide, whereas fractures in Comanche Peak and Georgetown limestones are usually less than 1 mm wide. In areas adjacent to major faults or flexures, the average fracture spacing for fractures with similar strikes ranges between 8.3 and 2.2 m in beds between 3.4 and 0.7 m thick. Limestone beds 1.0 to 1.5 m thick have an average fracture spacing range between 3.3 and 5.0 m. Fractures are usually not equally distributed across an area, and joints sometimes occur in narrow (1 to 5 m), closely spaced zones. Maximum joint densities average 3 to 4 joints/m in the closely spaced joint zones. Lateral and vertical connectivity of fractures is probably greater near major faults. Fractures in areas adjacent to faults may have high connectivity across faults as well as parallel faults. Springs near faults that discharge Edwards ground water that has migrated upward verify vertical fracture connectivity in areas adjacent to faults.

Hydrologic Conclusions

Hydrologic and hydrochemical data from the northern segment of the Edwards aquifer in the Balcones Fault Zone - Austin region were evaluated to characterize recharge and discharge mechanisms and the hydrochemical pattern observed in the aquifer. Regional ground-water flow is characterized by a relatively fast flow system with major discharge points along faults and fractures just east of the Edwards outcrop area. Some ground water bypasses these discharge sites and flows into the eastern part of the confining section of the aquifer. No distinct discharge sites exist and reduced transmissivities cause large fluctuations of water levels in the confined part of the aquifer. Discharge presumably occurs through leakage across the confining beds.

Water-level hydrographs from individual wells in the area, based on monthly measurements, show approximately synchronous variations in water levels within the fresh-water section of the aquifer. Water-level variations are relatively small in the outcrop section of the aquifer and increase to more than 100 ft in the confined section of the fresh-water aquifer. Continuous water-level records show some wells that respond very fast to individual recharge events, whereas others may show a more delayed response or none at all. A certain magnitude of rainfall appears to be necessary to trigger a discrete water-level response, which is dependent on the previous conditions regarding rainfall and water level. The water-level responses in wells 58-19-623 and 58-19-622 suggest local recharge by leakage along faults and fractures through the Georgetown Formation.

The hydrochemistry of the Edwards water indicates a chemical evolution of ground water from a calcium bicarbonate and calcium-magnesium bicarbonate to a mixed bicarbonate, and further downdip to a sodium bicarbonate, and finally to a sodium mixed type water. Tritium concentrations are relatively high in the shallow section, indicating ground water that was recharged in recent years. This pattern is consistent with the steeper hydraulic gradients in the western part, indicating relatively fast ground-water flow circulation. The concentration pattern of fluoride and nitrate suggests that the Del Rio Clay effectively confines the Edwards aquifer to the east, whereas the Georgetown outcrop belt is characterized as a more semi-confined section with relatively high nitrate concentrations. These elevated nitrate concentrations may point to shallow pollutant sources.

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