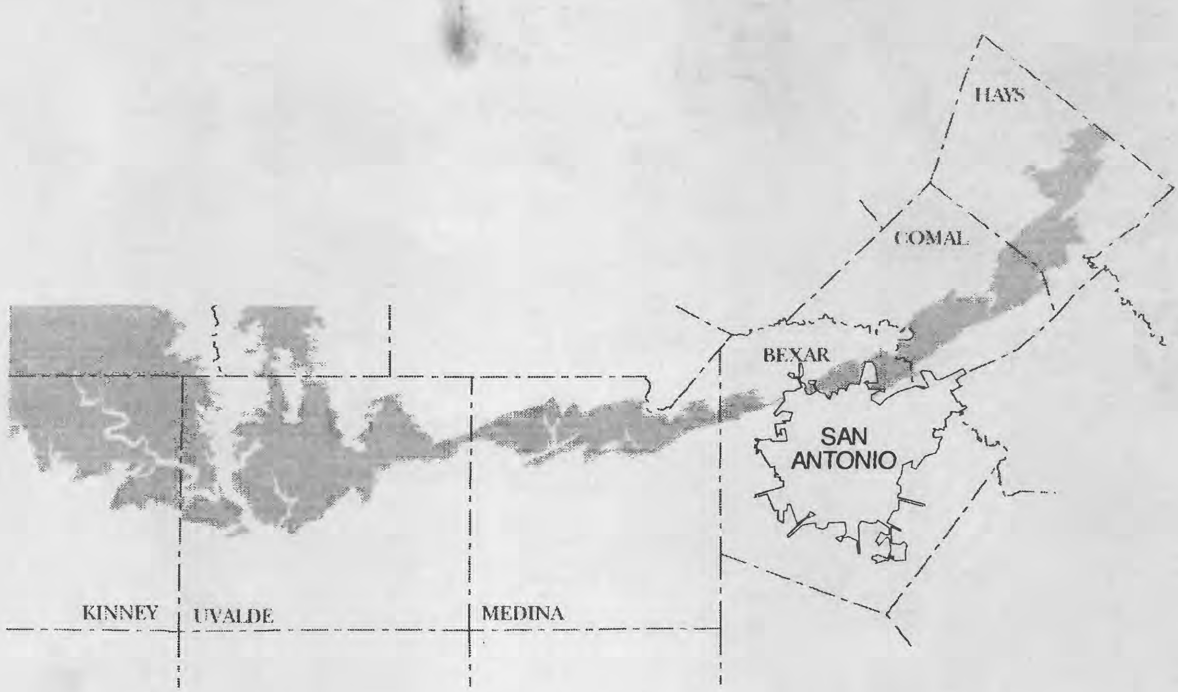
HYDROGEOLOGIC FACTORS THAT AFFECT THE FLOWPATH OF WATER IN SELECTED ZONES OF THE EDWARDS AQUIFER, SAN ANTONIO REGION, TEXAS

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 96–4046



Prepared in cooperation with the
SAN ANTONIO WATER SYSTEM

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By George E. Groschen

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Austin, Texas
1996

U.S. DEPARTMENT OF THE INTERIOR

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VERTICAL DATUM AND ABBREVIATIONS

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Per mil: A unit expressing the ratio of stable-isotopic abundances of an element in a sample to those of a standard material. Per mil units are equivalent to parts per thousand. Stable-isotopic ratios are calculated as follows:

$$\delta X = \left(\frac{R\,(\text{sample})}{R\,(\text{standard})} - 1 \right) \times 1{,}000,$$

where X is the name of the heavier stable isotope, and

R is the ratio of the heavier, less abundant stable isotope to the lighter stable isotope in the sample or standard.

The δ values for stable-isotopic ratios discussed in this report are referenced to the following standard materials:

Element	R	Standard identity and reference
oxygen	oxygen-18/oxygen-16 ($\delta^{18}O$)	Vienna-Standard Mean Ocean Water (Fritz and Fontes, 1980, p. 11)
hydrogen	hydrogen-2/hydrogen-1 or deuterium/protium (δD)	Vienna-Standard Mean Ocean Water (Fritz and Fontes, 1980, p. 13)

Abbreviations:

km, kilometer
km^2, square kilometer
m, meter
mm, millimeter
m^2, square meter
m^2/d, meter squared per day
m^3, cubic meter
ppt, part per thousand
TU, tritium unit

Hydrogeologic Factors that Affect the Flowpath of Water in Selected Zones of the Edwards Aquifer, San Antonio Region, Texas

By George E. Groschen

Abstract

The Edwards aquifer in the San Antonio region supplies drinking water for more than 1 million people. Proper development and protection of the aquifer is a high priority for local and State authorities. To better understand the flow of water in two major flowpaths in the Edwards aquifer, stratigraphic, structural, hydrologic, and geochemical data were analyzed. The western Medina flowpath is in parts of Uvalde, Medina, and Bexar Counties, and the eastern flowpath is in northern Bexar and central Comal Counties.

A major hydrogeologic factor that affects the pattern of flow in the Edwards aquifer is the spatial and temporal distribution of recharge. Other hydrogeologic factors that affect flowpaths include internal boundaries and the location and rate of spring discharge. The relative displacement of faults and the high permeability layers have substantial control on the discharge at springs and on the flowpaths in the Edwards aquifer.

Analysis of the estimated recharge to the Edwards aquifer during 1982–89 indicated that during years of substantial precipitation, a large part of the net recharge probably is diffuse infiltration of precipitation over large parts of the recharge area. During years with below-normal precipitation, most recharge is leakage from rivers and streams that drain the catchment subbasins.

In the western Medina flowpath, concentrations of major ions indicate saturation of calcite and undersaturation of dolomite—the two minerals that constitute most of the Edwards aquifer matrix. Concentrations of dissolved calcium, alkalinity, and dissolved chloride in the eastern flowpath are greater than those in the western Medina flowpath. These upward trends in concentrations might result in part from: (1) increased development in the recharge area, (2) mineralized effluent from developed areas, or (3) increased dissolution of aquifer material.

Tritium data from wells sampled in and near the western Medina flowpath indicate no vertical stratification of flow. Tritium concentrations in the recharge area of the western Medina flowpath are smaller than would be expected from previous studies and for the amount of recharge the area presumably received since 1952.

Stable-isotopic data indicate that the water in the Edwards aquifer is meteoric and, except in one known area, has not been subjected to substantial evaporation or other isotope-fractionating processes. Evaporation of water from Medina Lake results in a heavier stable-isotopic ratio in lake water, which subsequently recharges the Edwards aquifer. The stable-isotopic data indicate that lake water does not enter either of the two flowpaths.

INTRODUCTION

The Edwards aquifer in the San Antonio region supplies drinking water for more than 1 million people within most of a six-county region that includes Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties in south-central Texas (fig. 1). Proper development and protection of the aquifer is a high priority for local and State authorities. Comal and San Marcos Springs and the Edwards aquifer (fig. 1) are habitats for rare and endangered species (S. Hamilton, U.S. Fish and Wildlife Service, oral commun., 1993). Some of these

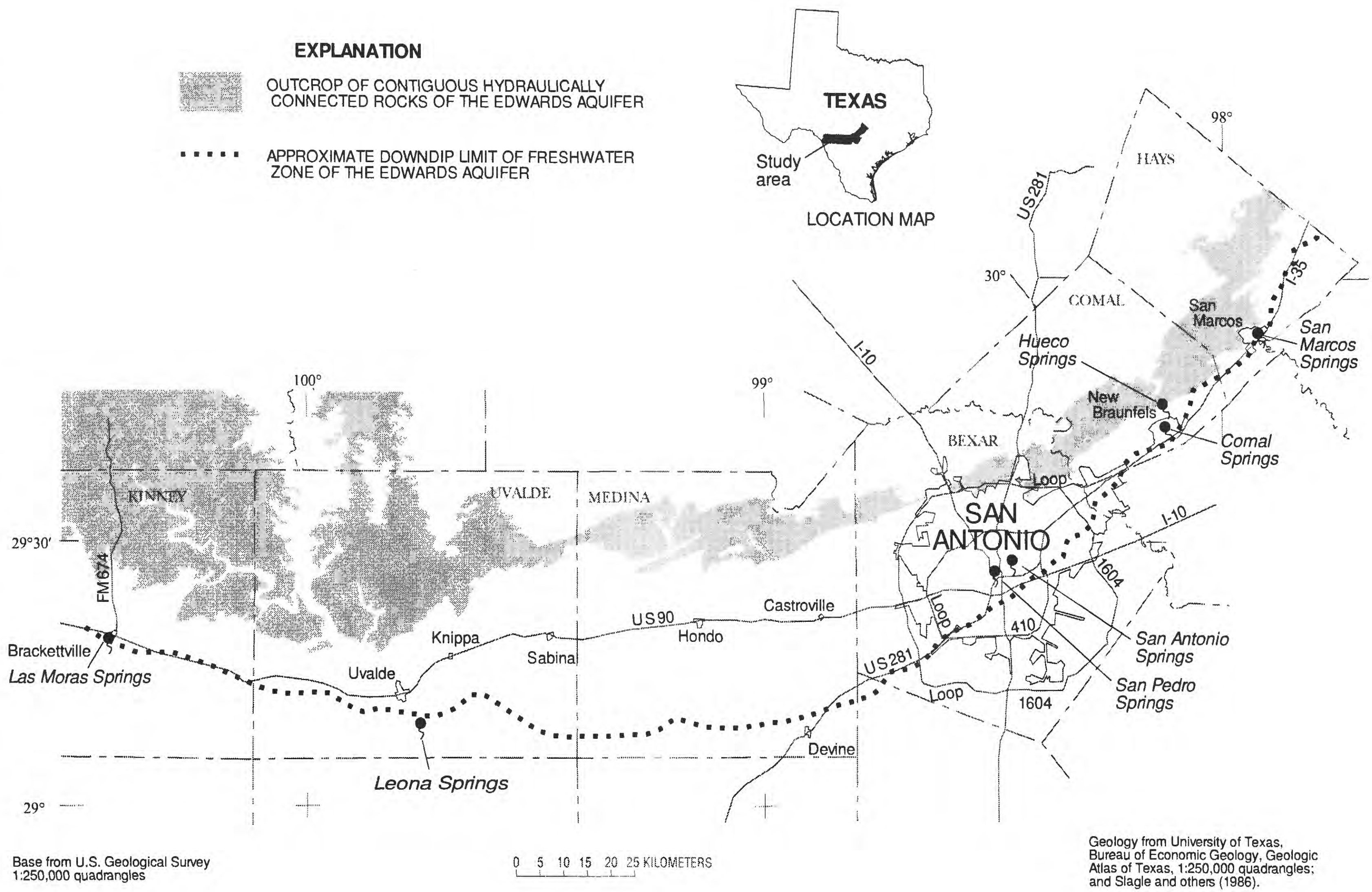


Figure 1. Location of the study area.

endangered species might be dependent on constant substantial flow at springs.

The Edwards aquifer primarily consists of limestone with some dolostone; however, the geologic structure and hydrostratigraphy are complex. Flow of water recharging the aquifer is assumed to be vertical through fractures and solution-enlarged holes or caves, or subhorizontal along bedding planes in the recharge or water-table area. The horizontal movement of water from the recharge area to the updip part of the aquifer (freshwater zone) is not fully understood. The water in the main freshwater part of the aquifer is confined between overlying and underlying low permeability strata, known as the confined zone.

Maclay and Small (1976, p. 23, table 1) defined eight hydrostratigraphic units within the rocks that compose the Edwards aquifer. Only three of the hydrostratigraphic units have high permeability. Most of the horizontal flow of water occurs within the high permeability layers of the aquifer. The same hydrostratigraphy also restricts vertical flow between high permeability layers, except where fault displacement has juxtaposed two high permeability layers that otherwise would not be contiguous.

Displacement of faults commonly offsets the high permeability layers against low permeability layers. Faults form barriers to horizontal flow where relative displacement is about one-half or more of the total aquifer thickness (Maclay and Small, 1984, p. 33). Maclay and Land (1988, p. 39) reported that the length and location of faults have substantial control on the discharge at springs and on the path that water follows from recharge to discharge.

Water from the recharge area in Medina County and part of Uvalde County flows parallel to fault barriers down into the deeper part of the confined zone to an area where the displacement along the fault decreases to less than about 50 percent of the total aquifer thickness (Maclay and Land, 1988, p. 38). Where the fault displacement is minimal, the water then moves around the barrier and flows toward the springs to the northeast, or is withdrawn by wells. In most of Bexar County and in all of Comal and Hays Counties, water in the aquifer flows generally parallel to faults (Maclay and Land, 1988, p. 20).

Proper development and protection of the ground-water resources depends on full understanding of the aquifer, including detailed knowledge of the distribution and movement of water within the aquifer. The U.S. Geological Survey (USGS), in cooperation with the San Antonio Water System, conducted a study to determine the major paths of ground water flowing in the San Antonio region.

Purpose and Scope

This report describes the major hydrogeologic factors that affect the pattern of flow in the Edwards aquifer and determines whether the flowpaths can be used to improve understanding of hydraulic and chemical gradients within selected zones of the aquifer.

The major objectives of the study were to obtain a detailed analysis of the hydrogeology, including the geologic structure and three-dimensional geometry of the Edwards aquifer and an analysis of the water levels and geochemistry along two selected flowpaths. The specific objectives of the report are: (1) to understand the hydrogeologic, structural, and stratigraphic characteristics of the Edwards aquifer and their effects on the flow of water; and (2) to interpret historical or current data within the framework of two major flowpaths delineated by previous studies.

The scope of this report covers the San Antonio region. The data used in this report were compiled primarily from previous investigations. Also, wells were sampled during the study and analyzed for concentrations of volatile organic compounds to trace the movement of recent recharge.

Methods of Investigation

Geologic data for the Edwards aquifer were obtained from previous investigations (Maclay and Small, 1976, 1984). Recharge estimates for 1982–89 were analyzed for each river or stream basin in the recharge area. The analyses of the recharge estimates helped determine the spatial and temporal distribution of recharge to the aquifer. The geologic data were compiled, checked, and edited for accuracy of location. The data then were entered into a spatial database/geographic information system (ARC/INFO) for verification and storage. Land-surface data were compiled from digital elevation models and digitized elevations were selected from U.S. Geological Survey 7–1/2-minute quadrangles. The geologic data and land-surface elevation data then were transferred to a contouring and graphic computer program.

A computer-based, geologic-surface modeling system was used to generate geologic-structure surfaces for the top of the Edwards aquifer from 1,818 verified data points. The number of control data points for the base of the aquifer were not as numerous as for the top of the aquifer. ARC/INFO was used to estimate values for all 1,818 data points used for the top surface from aquifer thickness determined at wells that penetrated the entire aquifer. These geologic-structure surfaces were verified for accuracy and consistency. Land-surface data were used to generate the outcrop of the Edwards aquifer. Geologic sections from Small (1986) were used to verify the accuracy and consistency of the data and to generate surfaces for the base, top, and outcrop of the aquifer.

Flowpaths in the Edwards aquifer were determined on the basis of geologic-surface-modeling analysis and work by Maclay and Land (1988). Two major flowpaths were selected for this study. Using computer-generated geologic surfaces, hydrogeologic sections were drawn along the center lines and also across the selected flowpaths. Available water-level data were plotted and contoured to help determine if the water-level gradient could be better understood when interpreted along the selected flowpaths. Major dissolved-ion concentrations along the selected flowpaths were used to determine any substantial geochemical changes of water in the aquifer. Tritium concentrations were used to help trace movement of water along a flowpath.

Data were interpreted from wells completed in the confined zone of the Edwards aquifer (Maclay and Small, 1976, 1984); therefore, the hydrostratigraphic definitions apply to the confined zone only. Unlike the confined zone, the outcrop of the Edwards aquifer recharge area has been subjected to more physical and chemical weathering. One of the selected flowpaths lies almost entirely within the recharge area. Therefore, it was necessary to determine if the hydrostratigraphy and fault-barrier concepts of the confined zone also apply to the recharge area. To better define the hydrostratigraphy and fault displacement in and near the recharge area, hydrostratigraphic units of Maclay and Small (1984), karst or karst-related features and faults, and associated displacements were mapped in the Edwards aquifer recharge area in Bexar County. Many of the faults in the Edwards aquifer area have displacement of 50 percent or more of the total aquifer thickness across the fault surface Maclay and Small (1984).

Selected wells and lakes in or near the study area were sampled early in the study to determine the utility of stable isotopes of oxygen and hydrogen in the water samples for tracing water movement. Historical water-level measurements of wells completed in the Edwards aquifer and historical and recent water-chemistry data were examined to improve understanding of the patterns of water movement from the Edwards aquifer recharge area. To help refine the flowpaths, 43 wells were sampled for volatile organic compound concentrations to determine their utility for tracing water movement within the selected flowpaths.

Well-Numbering System

The well-numbering system in Texas was developed by the Texas Water Development Board for use throughout the State. Under this system, each 1-degree quadrangle was given a two-digit number from 01 to 89. These are the first two digits of the well number. Each 1-degree quadrangle is divided into 7–1/2-minute quadrangles (similar to the 1:24,000 topographic quadrangle sheets), and each 7–1/2-minute quadrangle is assigned another two-digit number from 01 to 64. These are the third and fourth digits of the well identification number. Each 7–1/2-minute quadrangle is divided into 2–1/2-minute quadrangles numbered 1 through 9 for the fifth digit of the well number. As each well within a 2–1/2-minute quadrangle is inventoried (beginning about 1965), a number from 01 to 99 is appended to the one-digit 2–1/2-minute quadrangle for the last three digits of the well number.

In addition, each county in Texas is assigned a unique two-letter code. The county code is placed at the beginning of the well number. In the San Antonio region, the two-letter county codes include: AY, Bexar; DX, Comal; LR, Hays; RP, Kinney; TD, Medina; and YP, Uvalde.

Acknowledgments

Special thanks are extended to the municipalities and private well owners for allowing access to their wells for sampling. Thanks also are extended to the land owners in northern Bexar County who granted permission to enter their property. The author also thanks Mervin Klug, LBG–Guyton Associates, who provided helpful guidance throughout the study.

HYDROGEOLOGIC FRAMEWORK

Geology

The geologic formations that crop out in the Edwards aquifer are shown in figure 2. The stratigraphically equivalent units that compose the Edwards aquifer are the Kainer and Person Formations and overlying

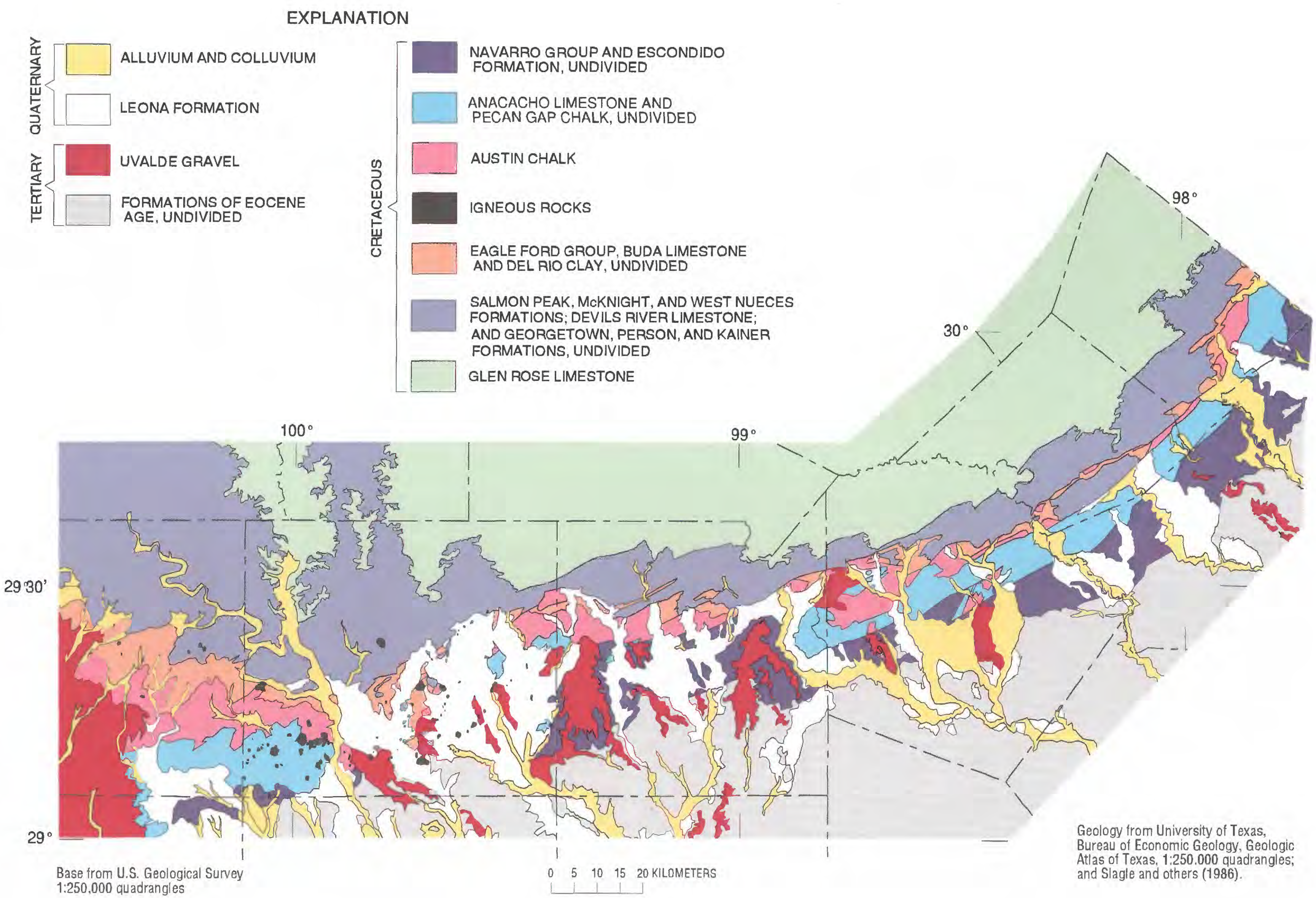


Figure 2. Surface geology of the Edwards aquifer in the San Antonio region, Texas.

Georgetown Formation in the San Marcos platform (Rose, 1972); the Devils River Limestone in the Devils River trend; and the West Nueces, McKnight, and Salmon Peak Formations of Lozo and Smith (1964) in the Maverick Basin. The correlation of stratigraphic units in south Texas and the Edwards aquifer hydrostratigraphic units in the San Marcos platform are shown in figure 3.

The Kainer Formation in the San Marcos platform comprises three informal members defined by Rose (1972, p. 65), and were later subdivided by Maclay and Small (1984) into four informal members (fig. 3). The Person Formation in the San Marcos platform comprises five informal members (Rose, 1972, p. 65). The Georgetown Formation overlying the Person Formation (fig. 3) is not known to yield water in the study area. However, because well drillers historically have considered the Georgetown Formation to indicate the top of the Edwards aquifer, the formation is considered part of the aquifer.

Lozo and Smith (1964) defined the Devils River Limestone in the Devils River trend (fig. 3) as rocks of the same stratigraphic interval as the Kainer, Person, and Georgetown Formations of the San Marcos platform, but without consistent markers to subdivide the formation. The West Nueces, McKnight, and Salmon Peak Formations in the Maverick Basin primarily are dense, homogeneous, fine-grained limestone and dolostone with little primary porosity (Lozo and Smith, 1964).

A series of faults (fig. 4) divides the Edwards aquifer into many smaller blocks. The vertical displacement along many of these nearly vertical to vertical faults is equal to or greater than one-half the aquifer thickness. The aquifer thickness ranges from about 120 m to more than 180 m (Maclay and Small, 1976). All the faults across the study area have combined displacement from about 300 to 400 m (Small, 1986).

The data points used to estimate the top surface of the Edwards aquifer (base of the Del Rio Clay) are shown in figure 5. The estimated top surface of the aquifer was compared to the original data by back-interpolating a value from the computed surface at the data control points. Residuals, the difference between the back-interpolated estimates and the actual data, were used to judge the goodness-of-fit of the top surface of the aquifer to the data. The standard deviation of the residuals is 7.1 m, and the mean square error is 51 m^2. Eighty-five percent (1,546) of the residuals are less than 1 standard deviation from verified data. The distribution of residuals that are greater than 1 standard deviation from the data is shown in figure 6. The areas where most large deviations from the data exist are where the top surface of the aquifer is complex—either intensively faulted such as in Bexar County, "hummocky" as in Uvalde County, or where the data density is high, such as parts of Bexar and Uvalde Counties.

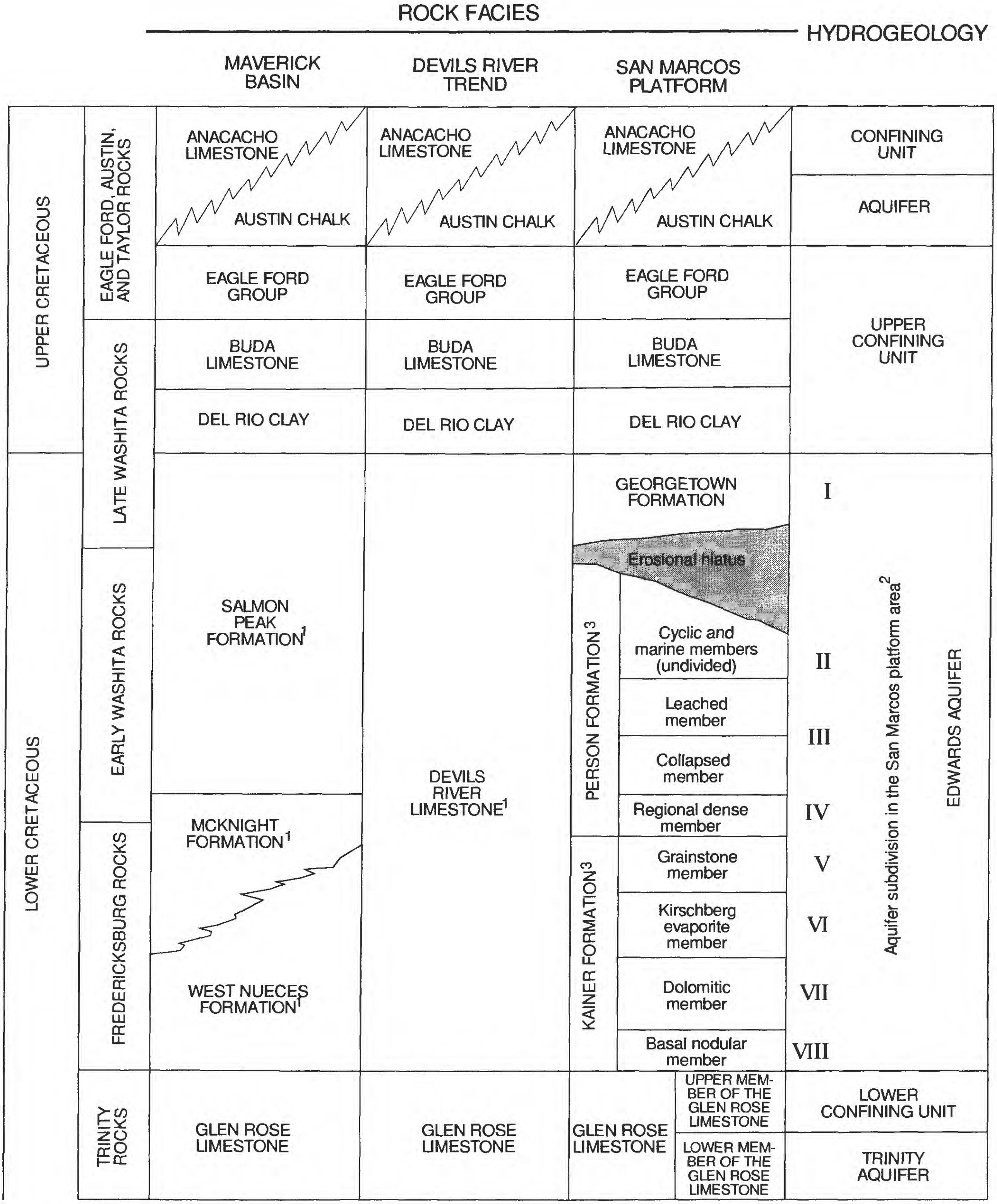
The data points used to estimate the base of the Edwards aquifer (top of the Glen Rose Limestone) are shown in figure 7. Because of the limited data points for the aquifer thickness, the goodness-of-fit was not evaluated. The calibration was considered adequate considering the scarcity of data for the base of the aquifer.

The base of the Del Rio Clay, selected faults, and contours of equal altitude are shown on plate 1. A similar view of the top of the Glen Rose Limestone showing faults and contours is shown on plate 2. Block sections illustrating the three-dimensional nature of the aquifer surfaces are shown on plate 3. Each block section is shown with the land surface displayed at the top of the block, and with the rocks younger than those of the Edwards aquifer removed to display the top of the Edwards aquifer at the top of the block.

The block sections displaying the top of the Edwards aquifer show several features (pl. 3). Block 1b in Uvalde County shows the top of the Edwards aquifer where there are few faults but great local relief, which might have resulted from the upward movement of molten rock in this area during the Late Cretaceous. Many outcrops of Upper Cretaceous or younger igneous rocks are in the area (fig. 2), and several plugs form hills on land surface (Welder and Reeves, 1964). Block 2b in Medina County shows the subsurface stair-step configuration resulting from fault movement in Medina County. Block 3b in Bexar County shows the Alamo Heights horst of Maclay and Land (1988, p. A42) and the complex top of the aquifer surface. Block 4b in Comal and Hays Counties shows the great displacement and length of the Comal Springs fault that stretches across the middle of the block. The narrow zone of freshwater that runs along the downthrown side of the Comal Springs fault also is shown.

Hydrology

The Edwards aquifer recharge area extends from San Marcos in Hays County to Brackettville in Kinney County (fig. 1). Garza (1966) reported a permanent ground-water divide to the west in Kinney County, east of Las Moras Springs (fig. 8). From Las Moras Springs,



1 Of Lozo and Smith (1964).
2 Maclay and Small (1984).
3 Modified from Rose (1972).

Figure 3. Correlation of Cretaceous stratigraphic units in south Texas and Edwards aquifer hydrostratigraphic units in the San Marcos platform area, San Antonio region, Texas.

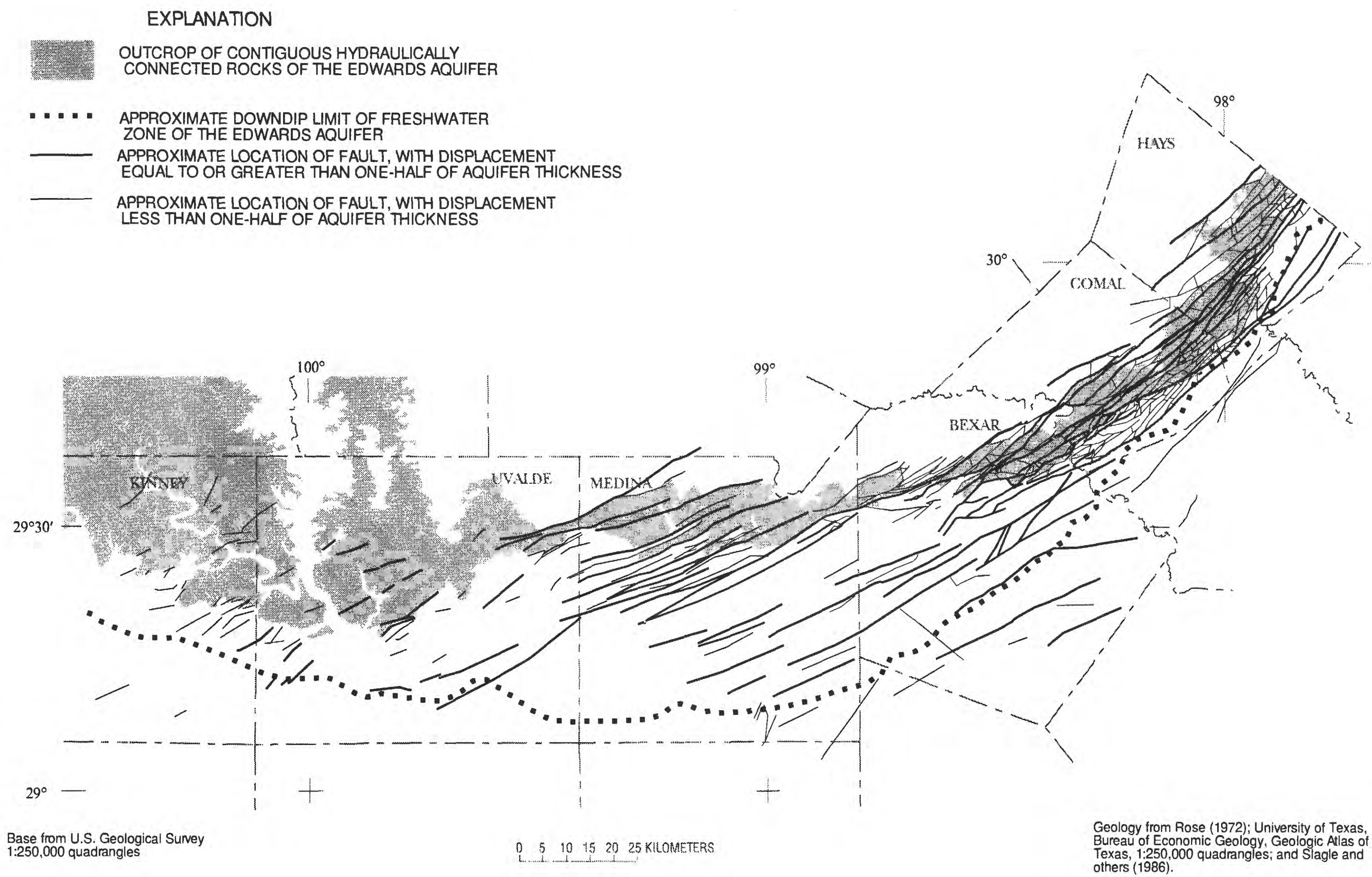


Figure 4. Locations of faults in the Edwards aquifer area, San Antonio region, Texas.

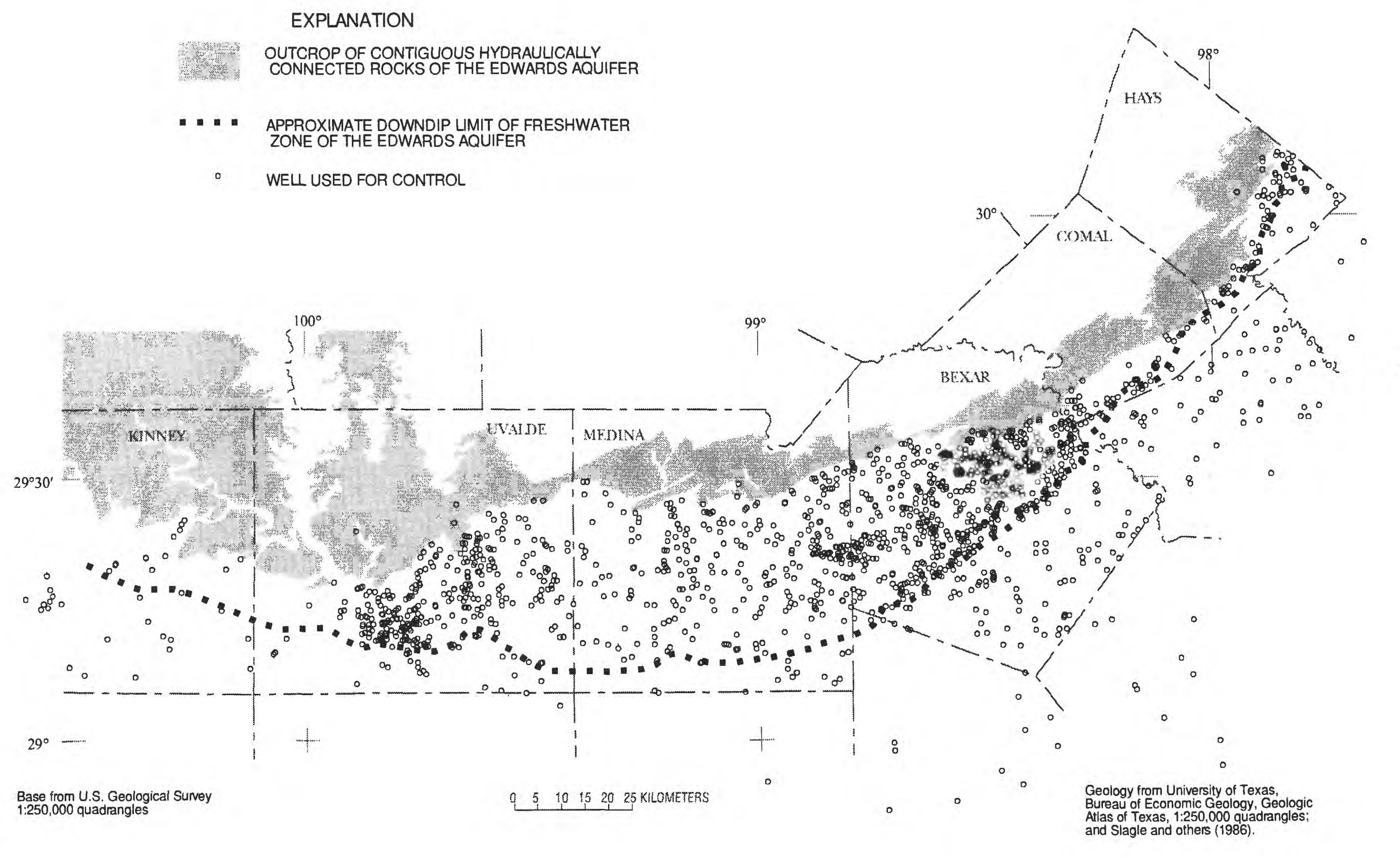


Figure 5. Locations of wells used to estimate the altitude of the base of the Del Rio Clay, San Antonio region, Texas.

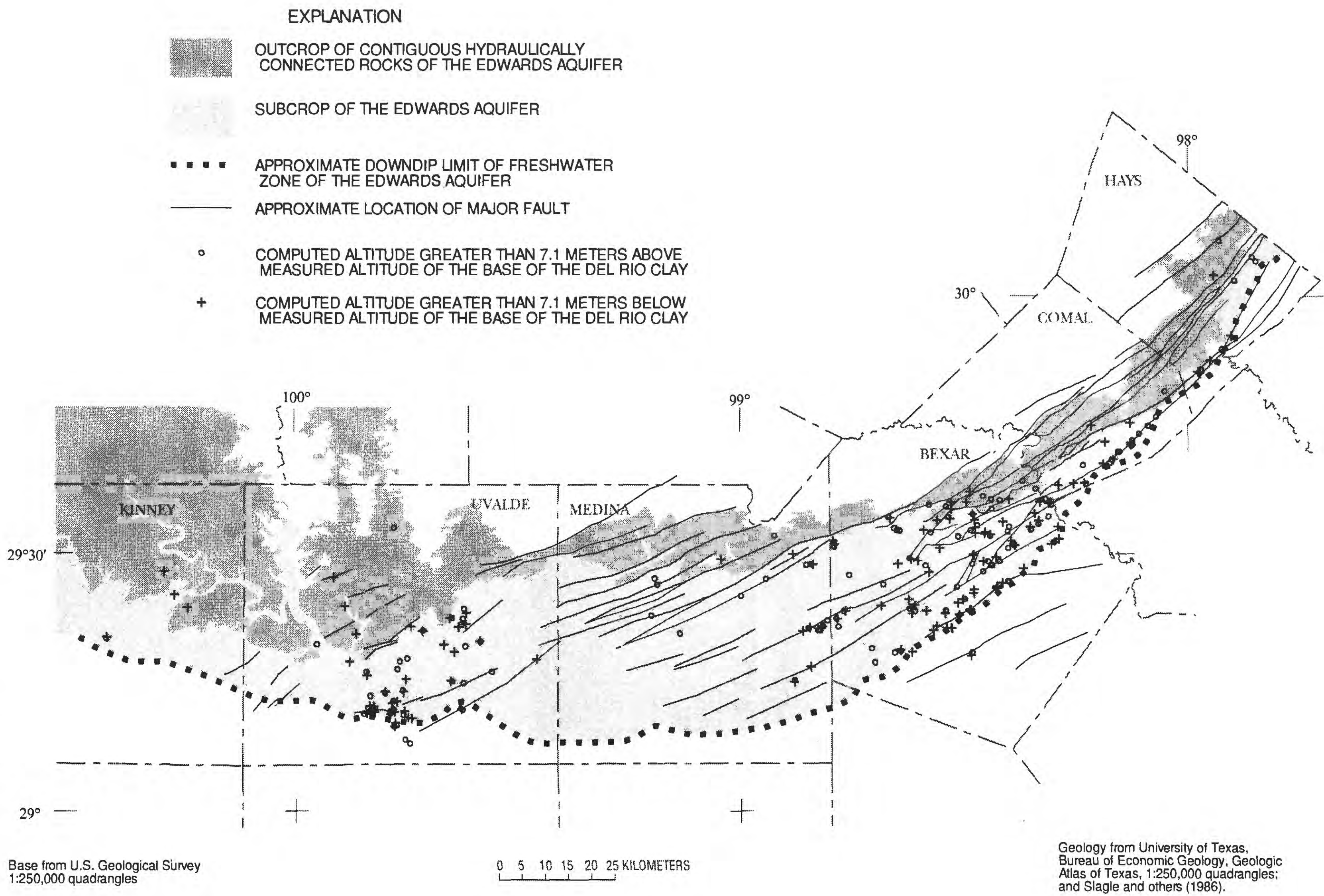


Figure 6. Locations of wells where computed altitude of the base of Del Rio Clay is greater than 7.1 meters above or below the measured altitude of the base in the subcrop of the Edwards aquifer, San Antonio region, Texas.

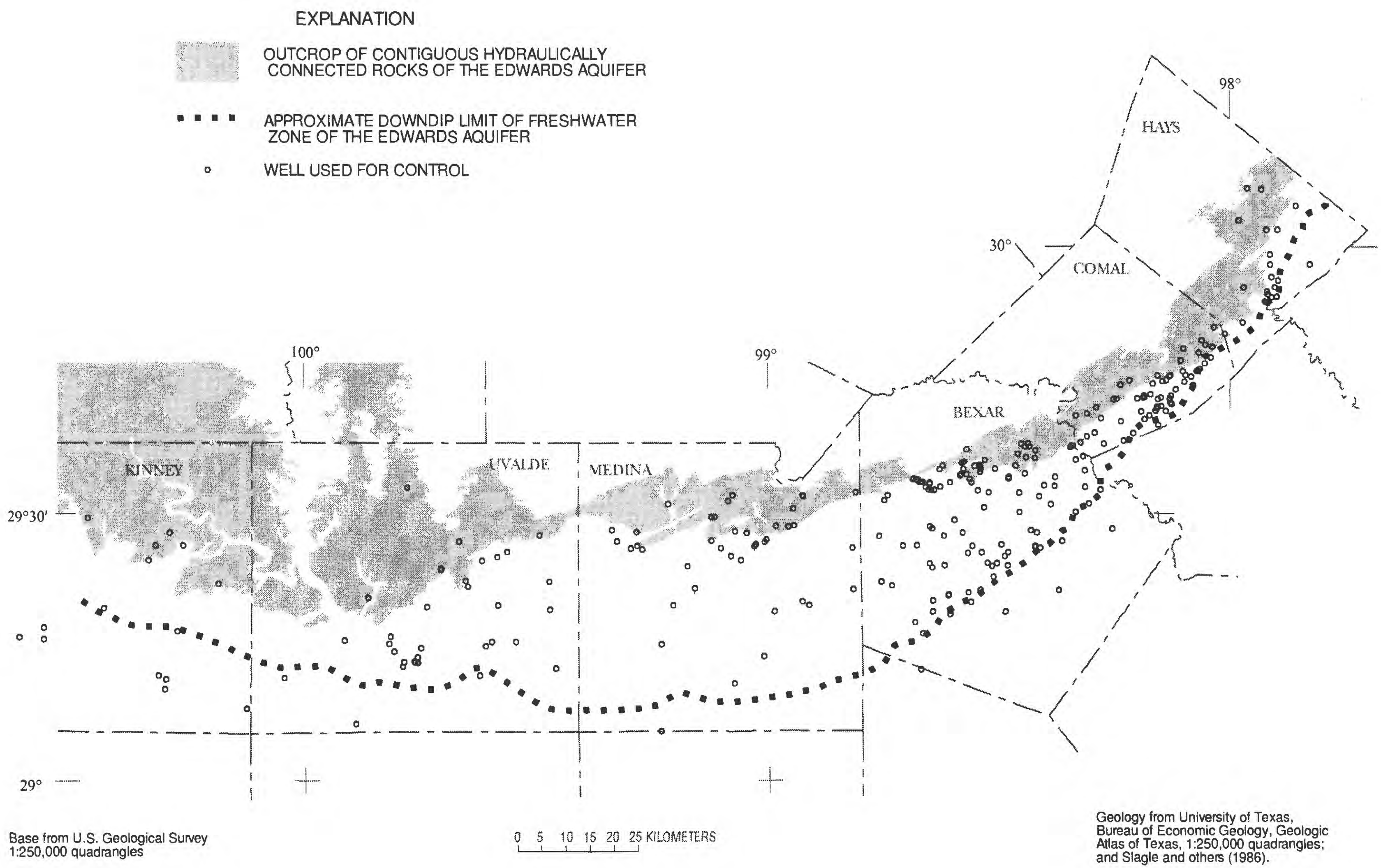


Figure 7. Locations of wells used to estimate the altitude of the top of the Glen Rose Limestone, San Antonio region, Texas.

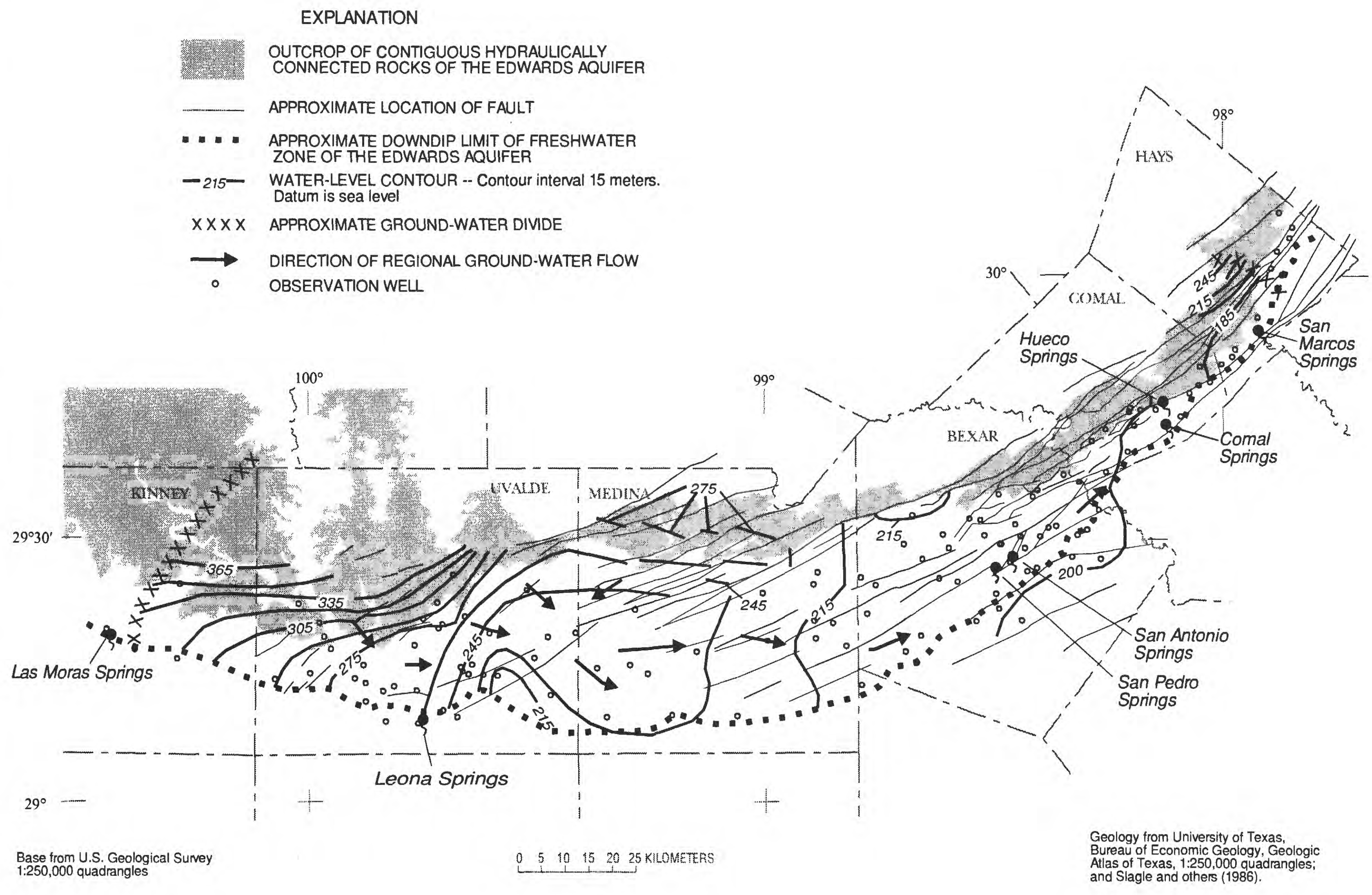


Figure 8. Locations of selected observation wells and faults, water-level contours for winter 1973, regional flow directions, and major springs of the Edwards aquifer, San Antonio region, Texas (modified from Maclay and Land, 1988, fig. 7).

the divide runs approximately north-northeasterly to the northern edge of the aquifer. Garza (1966) reported another permanent ground-water divide in Hays County northeast of San Marcos Springs.

The overlying Austin Chalk (fig. 3) yields water to domestic wells, especially in Medina and Uvalde Counties. The Austin Chalk aquifer might have hydrologic continuity with the Edwards aquifer where the two aquifers are structurally juxtaposed at faults. A similar relation exists between the Edwards and Trinity aquifers. Although substantial volumes of water might discharge from the Edwards aquifer through the Austin Chalk to land surface at the major springs, for this report, it is assumed that the Austin Chalk aquifer does not substantially affect the hydrology of the Edwards aquifer. The upper confining unit of the Edwards aquifer comprises the Eagle Ford Group, Buda Limestone, and Del Rio Clay (fig. 3).

The upper member of the Glen Rose Limestone (fig. 3) is assumed to be impermeable beneath the Edwards aquifer from the recharge area to the south and southeast (Maclay and Small, 1984). Because of large displacements along many faults, the Edwards aquifer is juxtaposed laterally to the lower member of the Glen Rose Limestone, which consists of the upper part of the Trinity aquifer (Maclay and Land, 1988, p. 16). In most of these zones of structural juxtaposition, hydrologic continuity is likely between the Edwards and Trinity aquifers, and the aquifers might act as a single hydrologic unit in these areas.

The water table in the Edwards aquifer outcrop area ranges from 30 m to greater than 90 m below land surface. Sections of the Kainer Formation, Devils River Limestone, and West Nueces Formation (fig. 3) that are less than about 60 m thick are assumed to be only partly or transiently saturated and not contributing substantially to the aquifer volume, and therefore are not included as part of the mapped area of the outcrop. The outcrop area of the aquifer discussed in this report is referred to as the outcrop of contiguous hydraulically connected rocks of the Edwards aquifer or "outcrop." Recharge estimates are based on the recharge area as outlined by Puente (1978, p. 3) and modified for consistency and comparability with historical data (Nalley and Thomas, 1990, p. 9).

Water-table conditions exist in the outcrop and for an undetermined extent into the zone where the aquifer is overlain by younger formations. Confined conditions exist where the aquifer is fully saturated and buried. Maclay and Land (1988, p. 36) reported that 60 to 70 percent of the aquifer is confined and includes most areas of discharge through springs and wells (fig. 8).

The volume of water in the aquifer depends on the temporal variations in recharge and discharge and on the antecedent conditions. The top of the saturated zone was estimated using water-level measurements made in 1952 (near or slightly below average conditions), 1958 (near average conditions), and 1989 (below average conditions). The 1989 measurements were made in August during a period of high ground-water withdrawals. The available data were insufficient to determine the regional water table following large recharge periods; therefore, the ranges in water levels represent dry to normal climatic periods only.

HYDROGEOLOGIC FACTORS THAT AFFECT FLOWPATHS OF WATER IN THE EDWARDS AQUIFER

A major hydrogeologic factor that affects flowpaths within the Edwards aquifer is the spatial and temporal distribution of recharge. The local climate typically is characterized by brief and infrequent large rainstorms that result in flash floods and high recharge pulses. The recharge from a storm can vary widely across the outcrop. The amount of precipitation that infiltrates to the water table in the large areas between stream channels, relative to the recharge from leakage through stream channels, is an important aspect of the spatial and temporal distribution of recharge. Other factors that determine flowpaths in the Edwards aquifer are internal boundaries formed by faults or aquifer geometry and the location and rate of spring discharge.

Spatial and Temporal Distribution of Recharge

The beginning of any ground-water flowpath is where recharge water percolates to the water table in the outcrop area. Recharge to the Edwards aquifer has been estimated since the mid 1950s. Annual recharge, by basin, has been estimated from 1934 (Garza, 1962) to the present. Historically, the water-table has received little intensive study; therefore, the understanding of the recharge process is limited.

Location of Recharge Area

The recharge area lies predominantly within and adjacent to the outcrop (fig. 1). Well-log data on geologic-unit thickness and water-level data for saturated thickness are insufficient to concisely map the hydraulically contiguous areas of the hydrostratigraphic units; therefore, the recharge area boundaries are approximate.

Estimation of Recharge Volumes

Annual and monthly recharge to the Edwards aquifer is estimated for each contributing river basin. The Nueces-West Nueces River Basin, Hondo Creek Basin, and Blanco River Basin (fig. 9) contribute recharge to the aquifer. Each basin is divided into three hydrogeologic divisions, but only two are used for estimating recharge. One hydrogeologic division used for estimating recharge is the Edwards aquifer recharge area. The other hydrogeologic division is the catchment area upstream from the recharge area. The catchment area catches the flow from springs and runoff from precipitation in the area and funnels it downstream toward the recharge area. Each stream or river basin is then divided into two subbasins—one that overlies the catchment area (catchment subbasin), and one that overlies the Edwards aquifer recharge area (recharge subbasin). The Trinity aquifer (Ashworth, 1983; Barker and others, 1994) underlies most of the catchment area, which also contains small erosional remnants of Edwards rocks that might contribute minor amounts of base flow to streams draining the catchment area. Most streams that flow over the recharge area are monitored by two streamflow gages. The upstream gage is near the area where the river or stream leaves the catchment area and enters the recharge area. The downstream gage is near the area where the stream leaves the recharge area.

Recharge is estimated by using: (1) streamflow data collected at upstream and downstream gages; (2) precipitation data collected in the catchment and recharge subbasins; and (3) empirical curves developed by Puente (1978) relating base flow measured at the upper gage to the amount of storage in the Trinity aquifer. A basic water-budget method can be computed using the following equation:

$$\textbf{inflow - outflow = change in storage} \qquad (1)$$

where

change in storage = recharge or increase in the amount of ground water in storage.

The different methods used to estimate recharge for each stream or river basin are listed in table 1. The estimated recharge for several ungaged basins is the product of the estimated recharge for the fully instrumented (precipitation and streamflow gages) basin and ratio of the area of the ungaged basin to that of the nearest fully instrumented basin.

The following streams and rivers that cross the recharge area are fully instrumented with field equipment to apply the basic water-budget method: the Nueces-West Nueces and Frio-Dry Frio River systems, Sabinal River, Seco Creek, Hondo Creek, and Blanco River (fig. 9). Several basins that are not fully instrumented, such as Salado Creek, are too large for approximating the recharge by analogy to a nearby fully instrumented basin. A modified version of the water-budget method is used to estimate recharge for these basins. The runoff for these basins is estimated by calculating unit runoff (estimated volume of runoff divided by gaged drainage area) from the nearest comparable continuous streamflow gaging station. The basin runoff for each large incompletely instrumented basin is the product of the estimated unit runoff from the nearby gaged drainage area and the ungaged drainage area. The recharge is estimated as the same fraction of flow past the lower gage as determined for an adjacent fully instrumented recharge basin. Hereafter, the discussion will cover only the recharge calculations for the six basins that use the water-budget method (table 1).

Calculation of the Water Budget to Estimate Recharge

Recharge to the Edwards aquifer is estimated by calculating a monthly water budget (eq. 1) for each basin. When no precipitation occurs in the recharge area for a month, the water-budget calculation consists of streamflow into the recharge subbasin minus that leaving the recharge subbasin. For months with no precipitation on the recharge subbasin, flow leaving the recharge subbasin is rare. Consequently, for a rainstorm greater than about 13 mm, the equation becomes more complex. The major factors in the water-budget equation include: (1) diffuse infiltration of precipitation in the recharge subbasin (precipitation that infiltrates immediately); (2) floodflow and base flow from the catchment subbasin (once precipitation reaches the recharge subbasin it leaks into the subsurface within the stream channel); (3) floodflow and base flow generated in the recharge subbasin (precipitation that does not immediately infiltrate, also called other direct recharge); and (4) surface-water outflow past the lower gage (also called rejected recharge). Net recharge is the total recharge to the Edwards aquifer minus the streamflow past the lower gage. Total recharge is the quantity

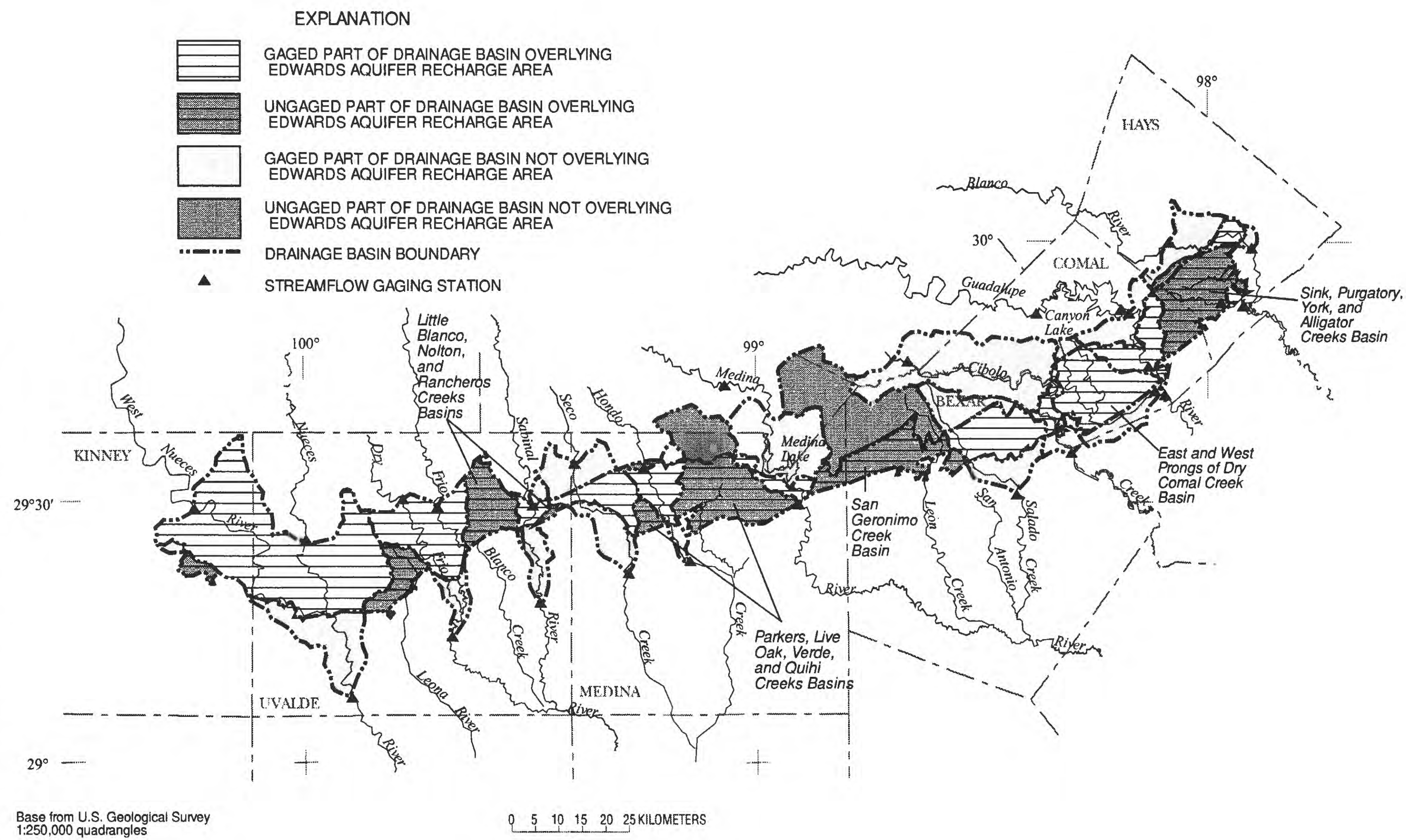


Figure 9. Locations of drainage basins over the Edwards aquifer recharge area, San Antonio region, Texas (modified from Puente, 1978).

Table 1. Summary of methods used to estimate recharge for stream or river basins in the Edwards aquifer recharge area, San Antonio region, Texas

[Water-budget method, inflow-outflow = change in storage]

Stream or river basin	Method used to estimate recharge
Nueces-West Nueces River	Water budget
Frio-Dry Frio River	Water budget
Leona River and Blanco Creek	Proportional to Frio-Dry Frio recharge subbasin
Sabinal River	Water budget
Little Blanco, Nolton, and Rancheros Creeks	Proportional to Sabinal River recharge subbasin
Seco Creek	Water budget
Hondo Creek	Water budget
Parkers and Live Oak Creeks	Proportional to Hondo Creek recharge subbasin
Verde and Quihi Creeks	Average of unit runoff from nearby streamflow-gaging stations times the area; recharge is same fraction of runoff estimated for Hondo Creek recharge subbasin
Medina River	Medina Lake and Diversion Lake recharge method of Lowry (1955)
San Geronimo and Leon Creeks	Average of unit runoff from two nearby streamflow-gaging stations times the area and adjusted for fraction of Salado Creek runoff estimated to be recharge
Salado Creek	Unit runoff of Cibolo Creek at Boerne streamflow-gaging station times the area of basin minus outflow at Salado Creek streamflow-gaging station below recharge area
Cibolo Creek	Unit runoff estimated from either Guadalupe River streamflow-gaging stations, or Cibolo Creek streamflow-gaging station below recharge area, whichever is greater, times the area minus outflow at downstream Cibolo Creek streamflow-gaging station
East and West Prongs of Dry Comal Creek	Unit runoff estimated from streamflow-gaging stations on Guadalupe River times the area minus outflow of Comal River after subtracting Comal Springs flow
Blanco River	Water budget
Sink, Purgatory, York, and Alligator Creeks	Unit runoff estimated from nearby streamflow-gaging stations times the area and adjusted to be same fraction of runoff estimated for Dry Comal Creek Basin

of water estimated to have reached the Edwards aquifer. Direct recharge is the sum of diffuse infiltration and recharge (floodflow and base flow resulting from the recharge subbasin).

Recharge by diffuse infiltration into the Edwards aquifer is not estimated because the available data are insufficient to compute recharge directly. The amount of diffuse infiltration of precipitation into the Trinity aquifer in the catchment subbasin is estimated by separation of storm hydrographs recorded at the upper gage and relating the difference in two distinguished base-flow quantities to increased ground-water storage in the catchment subbasin. Diffuse infiltration into the Edwards aquifer in the recharge subbasin is indirectly estimated by analogy to the catchment subbasin.

During months following unusually intense or extended precipitation, the streamflow out of the recharge subbasin is greater than the streamflow into the recharge subbasin. When this occurs, the net recharge is set to zero for the month because more water is leaving the recharge area than entering; therefore, ground water is being discharged from the Edwards aquifer in the recharge area. Total recharge is always calculated before determining the net recharge, even for months when the outflow past the lower gage is known to be greater than the inflow at the upper gage.

Precipitation that is insufficient (generally less than 13 mm) to produce storm runoff is assumed to yield only negligible quantities of recharge to the Edwards aquifer. The amount of infiltration resulting from this precipitation is sufficient only to replenish soil water storage and is not estimated. For those months when widespread or intense precipitation results in storm runoff, diffuse infiltration of precipitation falling directly on the recharge area is estimated. The data collected for estimating diffuse infiltration are streamflow at the upper and lower gages of the recharge subbasin and a variable number of precipitation measurements over the catchment and recharge areas.

Puente (1978) analyzed base flow from the catchment subbasins that had long historical records and developed a curve for each basin. The curve relates catchment subbasin base flow to volume of Trinity aquifer storage in the catchment subbasin using streamflow records of recessional periods with no precipitation and low evapotranspiration losses. Increases in Trinity aquifer storage are assumed to be diffuse infiltration from the precipitation that yielded the storm runoff.

The diffuse infiltration into the recharge subbasin for the rainstorm (in month-long segments) is equal to the increased volume of ground water estimated for the Trinity aquifer in the catchment subbasin with adjustments for the differences in drainage area and precipitation between the two subbasins. Diffuse infiltration in the Edwards aquifer recharge subbasin for the month is based on several factors: (1) catchment subbasin increased storage; (2) ratio of land area in the recharge subbasin to land area in the catchment subbasin; and (3) ratio of average precipitation in the recharge subbasin to average precipitation in the catchment subbasin.

Separation of the Streamflow Hydrograph to Determine Diffuse Infiltration

A storm hydrograph (fig. 10) recorded at the upstream gage is used to estimate the components of the water budget of the catchment subbasin. The hydrograph is distinguished into several components: (1) floodflow—runoff from precipitation that exceeds soil or rock storage; (2) base flow—the flow that would have passed the gage had the rainstorm not occurred (visually estimated by extrapolating the base flow recession prior to the rainstorm forward in time through the period of the storm hydrograph); and (3) increased base flow—the amount of streamflow assumed to have discharged to the stream from ground-water flow resulting from nearly instantaneous infiltration of precipitation (visually estimated by extrapolating the base-flow recession after the rainstorm backward in time through the storm hydrograph). Puente (1978) defined another storm hydrograph component called initial increased base flow; however, it is rarely significant in volume compared to the other components. Total volume of floodflow and base flow are estimated from the storm hydrograph. The instantaneous difference between base flow and increased base flow is estimated to relate to increased Trinity aquifer storage from the curves developed by Puente (1978).

Over time, base flow generally decreases slowly between rainstorms, so separating it on a storm hydrograph from other parts of the streamflow budget depends, to some extent, on the conceptual understanding of the hydrologic processes involved (Domenico, 1972, p. 42–53). The method used in separating the increased base flow from the other components of the streamflow hydrograph for a particular storm is based on Puente's (1978) analysis.

Estimates of Edwards aquifer recharge contain a substantial amount of uncertainty because the basic assumptions of the recharge estimation method are not verified. Small interpolation errors in graphically separating (extrapolating) hydrograph components lead to much larger errors in the estimated amount of increased storage in the Trinity aquifer in the catchment subbasin. The understanding of the Trinity aquifer has increased over the past few decades (Ashworth, 1983; Barker and others, 1994), and major differences in the hydrology between the Trinity aquifer and the Edwards aquifer are now identifiable.

First, the hydraulic characteristics of the Trinity aquifer indicate that it is capable of storing and transmitting much smaller quantities of water than the Edwards aquifer (Bush, 1986, p. 5). The Trinity aquifer is much less understood than the Edwards aquifer, and the differences in hydrologic characteristics between the two aquifers regarding Edwards aquifer recharge are unknown. The recharge rate is determined, in part, by the permeability of the aquifer. Because the Trinity has lower permeability than the Edwards aquifer, estimating Edwards aquifer recharge by comparing it to Trinity recharge would underestimate recharge because the Edwards aquifer could transmit more water from land surface to the water table faster than the Trinity aquifer.

Second, the water table in the Edwards aquifer generally is several meters to 100 m below land surface, even near streams, and commonly does not contribute base flow to streams in the recharge area. By contrast, the water table in the catchment area of the Trinity aquifer is close to land surface in most valleys, and the ground water contributes perennial base flow to streams through hundreds of small springs scattered throughout the recharge area of the Trinity aquifer (Ashworth, 1983, p. 48; Kuniansky, 1989).

Third, because the runoff characteristics are assumed identical between the catchment subbasin and the recharge subbasin, for consistency, floodflow and base-flow components are estimated by analogy for the recharge subbasin. Floodflow and base-flow

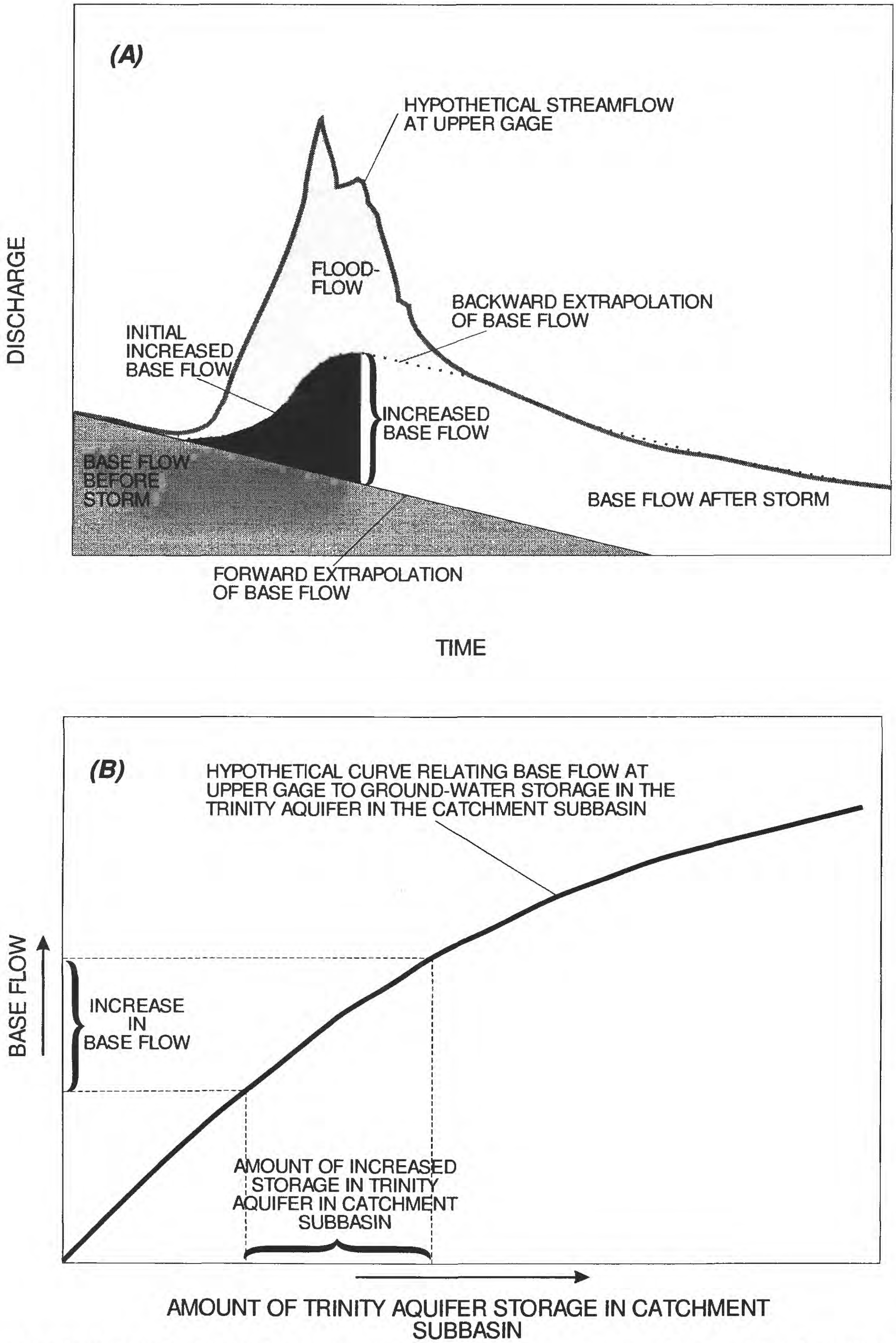


Figure 10. Hypothetical storm hydrograph separation of streamflow components (A), San Antonio region, Texas; and hypothetical relation of base flow to storage in the Trinity aquifer in a catchment subbasin (B), San Antonio region, Texas.

components are likewise adjusted for differences in area and precipitation. The Edwards aquifer recharge area rarely has any base flow because ground-water discharge from the Edwards aquifer is negligible in the recharge area. The downstream gages indicate little flow from the recharge subbasins, except after intense rainstorms; however, some floodflow occurs during intense rainstorms. The majority of the floodflow in the recharge subbasin probably infiltrates before reaching the main channel of the gaged stream or river. Base flow and floodflow typically are much smaller than diffuse infiltration in the recharge subbasin.

Nueces-West Nueces River and Hondo Creek Basins Recharge Volumes for 1982–89

The Nueces-West Nueces River and Hondo Creek Basins were selected for this analysis because they represent typical basin types in the recharge area. The Nueces-West Nueces River Basin yields large volumes of recharge to the Edwards aquifer (table 2) and has the largest area of outcrop of Edwards aquifer rocks (fig. 9). The net recharge estimates for the Nueces-West Nueces River Basin are listed only for months during 1982–89 that had sufficient precipitation to compute storm runoff. The Nueces-West Nueces River Basin should have a large relative proportion of diffuse infiltration and other direct recharge. The Hondo Creek Basin is more representative of other basins in terms of the amount of net recharge and the ratio of recharge area to net recharge (table 3). The Frio-Dry Frio River Basin is not used for this analysis, even though it yields the largest single-basin volume of recharge to the aquifer. The Frio-Dry Frio River Basin is not representative of the other recharge basins because it has a much smaller area of outcrop than the Nueces-West Nueces Basin.

Rejected recharge can occur when diffuse infiltration and streamflow into the recharge area are equal to, or greater than, the net recharge amount. This indicates rejected recharge, but does not indicate which components of the total recharge were rejected. On the basis of the assumptions of the recharge estimation method, diffuse infiltration must enter the aquifer first. In the catchment subbasin, diffuse infiltration of precipitation is considered to be nearly instantaneous, resulting in almost immediately increased ground-water discharge.

Because the recharge subbasin yields no actual base flow, the infiltration is actually either in transit to, or accreting to, the Edwards aquifer water table. Unlike the catchment subbasin, the increased storage in the Edwards aquifer does not result in base-flow increases because the water table is typically well below land surface. The increased storage in the Edwards aquifer probably does not increase ground-water discharge anywhere in the Edwards aquifer recharge area except at Hueco Springs, or in subbasins where the amount of diffuse infiltration alone exceeds the estimated net recharge. The latter condition is probable when outflow past the lower gage is much larger than inflow at the upper gage.

All estimated diffuse infiltration enters the Edwards aquifer, regardless of rejected recharge. When diffuse infiltration exceeds the amount of net recharge (greater than 100 percent), even some of the diffuse infiltration must be rejected or discharged from the Edwards aquifer following the recharge event. If precipitation or streamflow does not enter the aquifer during a rainstorm or is rejected shortly afterward, the water-budget component most likely to be rejected as recharge is the streamflow entering from the catchment subbasin.

Amount of Diffuse Infiltration Relative to Net Recharge and Streamflow

Diffuse infiltration actually comprises a large percentage of the net recharge for most large rainstorms such as during June 1987 in the Nueces-West Nueces River Basin (table 2). Streamflow from the catchment subbasin is a large part of the net recharge only during periods of little or no precipitation. Water volumes recharged during months with little or no precipitation comprise only a small part of the annual net recharge volume, except during years with below-normal precipitation.

The spatial and temporal distribution of recharge during 1982–89 was determined by analysis of the major components of the estimated recharge for the months that had substantial precipitation. The recharge during 1982–89 might not be representative of the long-term average for recharge to the aquifer, but that period does have a wide range of dry and wet years. The annual net recharge, direct recharge, and diffuse infiltration for Nueces-West Nueces River and Hondo Creek Basins for 1982–89 are listed in table 4. The reported annual precipitation for 1982–90 and the long-term average annual precipitation for 1883–1989 at San Antonio are shown in figure 11 as an indicator of the potential for recharge during each year.

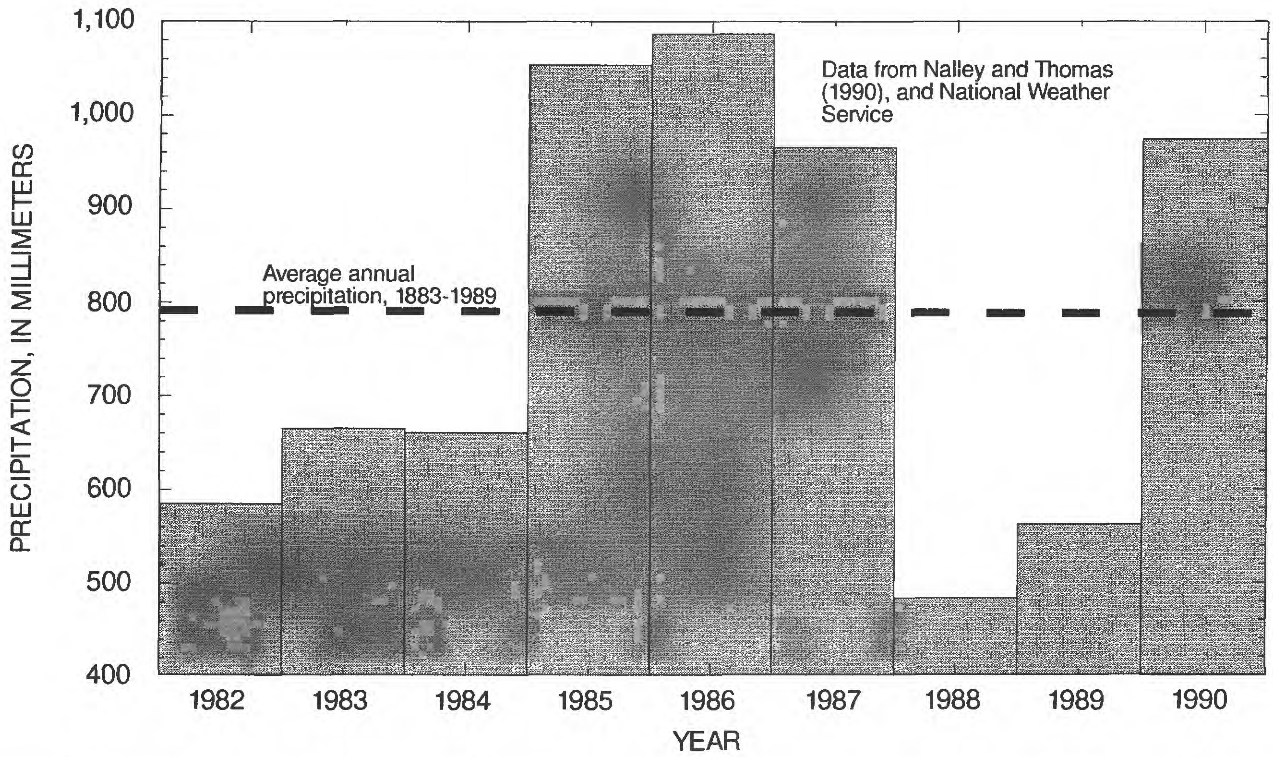


Figure 11. Annual precipitation for 1982–90 and the long-term average annual precipitation for 1883–1989, San Antonio, Texas.

During years with below-normal precipitation (1982–84, 1988, and 1989), recharge derived from the catchment subbasins is one-half or more of the net recharge in the particular basin (table 4). The diffuse infiltration of precipitation commonly is the largest component of recharge during the wet years in Nueces-West Nueces River and Hondo Creek Basins. In 1987, a year with intense rainstorms and above-normal precipitation during the first one-half of the year, 87 and 33 percent of the annual net recharge to Nueces-West Nueces River and Hondo Creek Basins, respectively, was estimated to have resulted from diffuse infiltration of precipitation (table 4).

Implications of Recharge Distribution on Flowpaths

The distribution of recharge over space and time directly affects the patterns of flow and regional flowpaths in the Edwards aquifer. The spatial and temporal distribution of recharge to the Edwards aquifer might directly or indirectly determine the source of dissolved constituents or contaminants and probably the fate of these contaminants. If stream-channel leakage is consistently the major contributor of recharge, the chemistry of the streamflow from the catchment subbasin will have a direct and immediate effect on the chemistry of water in the recharge area of the Edwards aquifer. The aquifer matrix surface area in contact with the percolating water under the stream channel would be small and the transit time between land surface and the water table probably would be short because the water table is closest to land surface under streams. Therefore, potential contaminants in the recharge water probably would be attenuated only slightly or unchanged when it reaches the aquifer below the stream channel.

The geochemical environment under stream channels would be much different than in the zone between stream channels where slower diffuse infiltration occurs. If diffuse infiltration is the predominant source for a substantial volume of the recharge water, the movement of water downward to the water table would probably be slower than it would be under stream channels. Therefore, the chemistry of precipitation and resulting water-rock interactions in the large unsaturated zone above the water table between stream channels would have the greatest effect on the chemistry of

Table 2. Estimated monthly recharge to the Edwards aquifer for Nueces-West Nueces River Basin, San Antonio region, Texas, 1982–89[1]

Month	Year	Net recharge estimate (millions of cubic meters)	Diffuse infiltration	Other direct recharge	Streamflow: Into recharge basin	Streamflow: Out of recharge basin
			(Percentage of net recharge estimate for month)			
May	1982	3.7	440	89	360	780
May	1983	7.3	49	8.4	62	20
June	1983	20	24	1.8	95	21
September	1983	10	78	5.0	28	12
November	1983	19	66	23	21	9.6
October	1984	7.5	80	13	20	14
November	1984	14	68	12	25	4.8
January	1985	6.6	380	230	240	760
March	1985	25	79	12	56	47
June	1985	9.6	40	17	76	33
July	1985	11	49	25	81	56
November	1985	28	80	15	28	23
February	1986	7.6	40	2.6	87	30
May	1986	41	88	1.7	14	4.5
June	1986	26	67	6.6	55	28
September	1986	50	84	16	8.6	9.1
October	1986	43	100	29	61	94
November	1986	24	92	14	95	100
December	1986	26	85	7.1	68	60
January	1987	30	84	4.3	67	55
February	1987	14	62	4.2	100	71
March	1987	17	69	6.0	97	72
April	1987	15	62	4.4	100	67
May	1987	27	100	79	190	270
June	1987	250	92	25	49	66
September	1987	23	81	30	210	220
December	1987	3.6	130	7.6	320	360
May	1988	7.4	60	4.1	82	46
June	1988	21	65	7.9	43	15
July	1988	14	34	5.0	100	41
August	1988	8.7	50	.7	92	43
September	1988	9.2	68	3.0	60	31
January	1989	14	77	3.6	36	16
February	1989	9.2	53	2.5	65	20
March	1989	7.6	35	1.7	88	25
May	1989	6.4	50	1.6	73	24
November	1989	14	63	7.2	35	5.3

[1] Recharge estimates are only for those months that had sufficient precipitation to compute storm runoff.

Table 3. Estimated monthly recharge to the Edwards aquifer for Hondo Creek Basin, San Antonio region, Texas, 1982–89[1]

Month	Year	Net recharge estimate (millions of cubic meters)	Diffuse infiltration	Other direct recharge	Streamflow: Into recharge basin	Streamflow: Out of recharge basin
			(Percentage of net recharge estimate for month)			
May	1982	11	44	24	32	0
March	1983	3.0	59	16	25	0
May	1983	3.5	45	36	20	.7
June	1983	4.5	52	67	48	68
November	1983	1.4	34	20	45	0
January	1985	12	40	40	22	1.9
March	1985	9.9	27	30	45	2.0
May	1985	11	27	48	40	14
October	1985	6.9	57	44	14	15
December	1985	3.9	24	11	64	0
May	1986	2.2	31	8.8	60	0
June	1986	6.2	42	50	42	34
September	1986	2.7	30	5.4	64	0
October	1986	9.2	38	39	32	8.7
November	1986	6.0	19	6.4	74	0
December	1986	13	38	28	44	11
March	1987	12	31	13	56	0
May	1987	14	15	120	220	250
June	1987	77	50	51	100	100
August	1987	3.3	20	2.0	78	0
November	1987	1.6	32	7.1	61	0
December	1987	1.6	34	8.0	58	0
July	1988	3.1	17	16	74	6.2
September	1988	.8	32	6.0	62	0
October	1989	2.0	44	18	38	0

[1] Recharge estimates are only for those months that had sufficient precipitation to compute storm runoff.

Table 4. Edwards aquifer annual net recharge, direct recharge, and diffuse infiltration for Nueces-West Nueces River and Hondo Creek Basins, San Antonio region, Texas, 1982–89

[Annual net recharge is the estimated recharge for the year; direct recharge is the sum of diffuse infiltration and other direct recharge (floodflow and base flow)]

Year	Annual net recharge (millions of cubic meters)	Direct recharge (millions of cubic meters)	Diffuse infiltration (percentage of net recharge)	Annual net recharge (millions of cubic meters)	Direct recharge (millions of cubic meters)	Diffuse infiltration (percentage of net recharge)
	Nueces-West Nueces River Basin			Hondo Creek Basin		
1982	24	3.7	15	17	4.8	28
1983	98	29	30	18	6.2	34
1984	40	15	38	3.7	0	0
1985	100	59	59	61	15	25
1986	230	190	83	47	14	30
1987	380	330	87	140	46	33
1988	73	33	45	8.2	.8	10
1989	65	30	46	5.0	.9	18
Cumulative recharge for 1982–89	1,000	690	69	300	88	29

water in the recharge area. Inferring that much of the Edwards aquifer recharge typically is spread over most of the recharge area, and only in dry periods is the recharge restricted to the stream channels, implies that tracing water through the recharge area and then toward discharge areas is complex.

Internal Flow Boundaries

After recharge enters the subsurface, factors such as bedding planes, dissolution porosity, and fractures and faults can affect the movement of water in the Edwards aquifer. Caves comprise a wide range of sizes of dissolution porosity. Veni (1988) reported that few caves in the outcrop area in Bexar County appear to have developed along faults. Veni (1988) also reported that caves did appear to have developed along fractures and concluded that there were sufficient fractures to account for the abundance of caves and other karst features. Many caves and sinkholes in the outcrop area are short pathways for recharge to the Edwards aquifer.

Recharge occurs more frequently in western Medina and northern Uvalde Counties where there are fewer faults than in Comal and Hays Counties where the aquifer is intensively faulted (fig. 9) and where precipitation, on the average, is greater (Carr, 1967). Part of the discrepancy in recharge from west to east results from the smaller area of outcrop and deeper entrenchment of streams in the eastern area. Therefore, the lack of cave development along faults and the disparity in recharge from west to east imply that it is likely that faults in the outcrop area and, by inference, the confined zone, generally are not vertical pathways for water movement. Exceptions exist where fault displacement juxtaposes permeable layers of the Edwards aquifer against permeable Austin Chalk layers where the Austin Chalk lies at or near land surface. Major springs are present at all known exceptions.

Fault surfaces in the Edwards aquifer typically are impermeable to vertical water movement; otherwise, the faults probably would provide pathways for water to flow into adjacent aquifers or to land surface. These conditions are not observed at most faults that are lateral flow barriers. Some faults that are not near springs might provide vertical or horizontal flowpaths because of the possibility of narrow breccia zones along the fault surface that might be inherently more permeable or more susceptible to dissolution than the surrounding rocks (T.A. Small, U.S. Geological Survey, oral commun., 1986).

Location and Rate of Spring Discharge

The last two factors that influence the direction of flow in the Edwards aquifer are the location and rate of flow to points of discharge. Although one-half or more of the discharge from the aquifer is withdrawals from wells (Nalley and Thomas, 1990), the springs have existed for a much longer time and have had a greater effect on developing the flow patterns than the wells. Geologic and hydrologic factors are less important for well location than for natural outlets, thus the wells are more evenly distributed over most of the aquifer area than the natural outlets. Therefore, the springs and springflow, rather than well withdrawals, are emphasized as major regional controls of flow direction even though wells will continue to have an increasingly important effect on local flow directions.

The rocks forming the Edwards aquifer are impermeable and do not allow substantial water flow, except where secondary dissolution porosity exists (Maclay and Small, 1984). Most secondary porosity occurs within stratigraphically limited layers (Maclay and Small, 1984). Vertical movement is limited, especially in the confined zone. Most natural discharge from the aquifer is through a few large springs (fig. 8). To an uncertain extent, the locations of these springs are determined by the locations of faults with large displacements. According to Woodruff (1977), one or more of these springs have been near their present location since about the Miocene Epoch. During the Miocene Epoch, movement along many of the faults in the area began or recurred (Weeks, 1945).

A negligible quantity of water (Maclay and Land, 1988) in the Edwards aquifer probably moves into overlying confining units by diffuse upward leakage. Ground water in the Edwards aquifer also moves into overlying aquifers where they have been laterally juxtaposed by fault displacement. Flow into these overlying aquifers and to land surface occurs at most of the major springs. Other than major springs, subsurface discharge from the Edwards aquifer probably is negligible.

San Antonio and San Pedro Springs

San Antonio and San Pedro Springs (fig. 8) rise along the downdip edges of the Alamo Heights horst (pl. 3, block 3b). The Alamo Heights horst was displaced upward with respect to the surrounding area, juxtaposing impermeable older rocks in the lower part of the horst block against the highly permeable layers of the Edwards aquifer surrounding the block. The impermeable older rocks are either nonporous layers of the Edwards aquifer or, more likely, the Glen Rose Limestone. The displacement of the Alamo Heights horst, relative to the lower permeable layers of the aquifer, is about 140 m at the southwestern corner and much less toward the northeast.

The exact flowpath between the Edwards aquifer and San Antonio and San Pedro Springs is uncertain. The flowpath might be a circuitous route, zigzagging between permeable layers in the Edwards aquifer and permeable layers in the Austin Chalk until the water discharges at land surface. Allan (1989) described fault-related fluid movement in oil-containing aquifers where oil, because of buoyancy effects, can follow such a zigzag path to an overlying geologic structure where the oil accumulates. Lateral juxtaposition of permeable layers of two or more aquifers could develop a similar path for water with sufficient hydraulic-head gradient to reach land surface.

The Austin Chalk and the Edwards aquifer might be hydrologically connected by juxtaposition at faults, such as the southwestern corner of the Alamo Heights horst. Livingston and others (1936, p. 70) reported that wells tapping the Austin Chalk aquifer are known to fluctuate in unison with the Edwards aquifer, especially near faults. Hydraulic continuity between the Austin Chalk aquifer and the Edwards aquifer implies that water takes a tortuous path from the Edwards aquifer within the horst, then through the Austin Chalk aquifer to land surface. San Pedro and San Antonio Springs issue from faults that have Austin Chalk at land surface on the downthrown side. An alternative hypothesis is that flow might simply move upward through a near-vertical conduit from the Edwards aquifer to the surface with little or no hydrologic involvement of the Austin Chalk aquifer. Available data are insufficient to determine the validity of either hypothesis.

Comal and San Marcos Springs

The two largest springs, Comal and San Marcos (fig. 8), account for most of the natural discharge from the Edwards aquifer, but they appear to be unrelated to blockage by upthrown fault blocks like San Antonio and San Pedro Springs. However, the faults where both sets of springs issue have substantial displacements (thickness of the aquifer or greater), and Austin Chalk lies at or near land surface near the springs (Small, 1986, figs. 3, 4). An unnamed fault intersects the Comal Springs fault at an acute angle. The intersection of these two faults might be important in creating an obstruction, or zigzag pathway between juxtaposed permeable layers and aquifers to land surface near the spring orifices (R.W. Maclay, retired, U.S. Geological Survey, oral commun., 1987). Not all of the flow in the narrow confined freshwater zone (pl. 3, block 4b) in Comal County is discharged at Comal Springs. One-half or more of the flow at San Marcos Springs flows past Comal Springs from the southwest (Pearson and others, 1975; Puente, 1976).

A hypothesis for the existence of San Marcos Springs, caused by fault displacement and juxtaposition of the Edwards and Austin Chalk aquifers, is supported by a series of structural features east-northeast of the spring orifices. Two fault blocks formed by the Comal Springs fault, the San Marcos Springs fault, and a major fault immediately west-northwest from the San Marcos Springs fault (pl. 3, block 4a), plunge downward to the east-northeast into the subsurface. Also, another series of faults through the Edwards aquifer in Hays County translate to the northwest just north-northeast of the San Marcos Springs (Grimshaw and Woodruff, 1986, p. 72). This is shown by the northward offset of the outcrop area of the Kainer and Person Formations in central and northern Hays County (pls. 1, 2).

Leona Springs

Leona Springs near Uvalde (fig. 8) is a series of small seeps that might or might not be associated with faults. Many subsurface plugs of igneous rock breach the Edwards aquifer over most of southern Uvalde County, especially in the Leona Springs area. The low permeability of these plugs could obstruct flow to the east. The Devils River Limestone, Salmon Peak, McKnight, and West Nueces Formations that compose the Edwards aquifer in Uvalde County lie close to land surface in south-central Uvalde County. In some areas, the formations form domes that penetrate the overlying rocks and expose the formations at land surface (pl. 3, block 1a).

Leona Springs is near the southern end of an inferred structural ridge in the subsurface formations southeast and east of Uvalde known as the Uvalde salient (Welder and Reeves, 1964, p. 27). Overlying the Uvalde salient, the upper confining unit—Eagle Ford Group, Buda Limestone, and Del Rio Clay (fig. 3)—is discontinuous or absent locally. The area also is overlain by the Leona Formation (fig. 2) that yields large quantities of water to wells in parts of Uvalde County, especially in the area between the Nueces and Leona Rivers (Welder and Reeves, 1964, p. 24). Leona Springs flow might result from the water table intersecting the top of the Edwards aquifer during periods of high recharge or low rates of well withdrawals. The Edwards aquifer discharges to the variably saturated Leona Formation, which in turn discharges into the Leona River.

The Austin Chalk aquifer provides water to a number of wells in Uvalde County (Welder and Reeves, 1964) and lies at or near land surface near the springs. Faults might juxtapose the Edwards and Austin Chalk aquifers near the springs creating a flowpath for water to land surface. However, the geology of the Leona Springs area is not as well defined as the area around the other major springs because of the widespread gravel deposits overlying the bedrock and the complexity of the geology.

Hueco Springs

Hueco Springs (fig. 8) is in central Comal County. The small group of springs and seeps is near the Guadalupe River about 5 km north-northwest of Comal Springs. Hueco Springs is the only large spring in the Edwards aquifer outcrop; therefore, it has a much smaller associated recharge area than any of the other major springs in the Edwards aquifer. Many small springs flow where the Edwards aquifer is at land surface, but only Hueco Springs is considered large enough to measure periodically. The springflow is widely variable and the springs do not flow during prolonged dry periods.

HYDROGEOLOGIC CHARACTERISTICS OF SELECTED FLOWPATHS OF WATER IN THE EDWARDS AQUIFER

Several flowpaths transmit recharge to the Edwards aquifer, but only two were selected for intense study. The western Medina flowpath (fig. 12), as delineated by Maclay and Land (1988), is in parts of Uvalde, Medina, and Bexar Counties. The eastern flowpath was selected for the eastern part of the aquifer because it lies almost entirely within the recharge area in northern Bexar and central Comal Counties.

Western Medina Flowpath

The largest of two areas that transmit recharge from the western part of the Edwards aquifer is the flowpath from the Nueces-West Nueces and Frio-Dry Frio River Basins (fig. 9). The flowpath from these basins is in one of the least understood parts of the Edwards aquifer, particularly in the Uvalde area; therefore, this flowpath was not selected for further study. The western Medina flowpath (Maclay and Land, 1988) is the other large area that transmits recharge west of San Antonio, and therefore, was selected.

Location and Geometry

The western Medina flowpath was outlined by Maclay and Land (1988) primarily on the basis of results of aquifer simulations of ground-water flow in the Edwards aquifer. The western Medina flowpath comprises the western Medina storage unit and the south-central flow unit of Maclay and Land (1988, fig. 22).

The northeastern (distal) boundary of the western Medina flowpath is poorly defined. Tracing the western Medina flowpath northeast of the Alamo Heights horst (fig. 13) is difficult because: (1) recharge occurs periodically near the Alamo Heights horst from surface runoff into San Antonio Springs; and (2) substantial quantities of water are withdrawn through wells in central Bexar County.

The western Medina flowpath is not bound on all sides by faults of large displacement. However, the number of faults that probably are flow barriers around or within the flowpath area are sufficient to effectively restrict the flow of water within the flowpath. The primary structures associated with the western Medina flowpath include the Medina Lake fault, the recharge area, the faults parallel to the Medina Lake fault in Medina County, and the Castroville fault (fig. 13).

Hydrogeologic sections of the subsurface in and adjacent to the western Medina flowpath show the geometry of the Edwards aquifer in the western Medina flowpath and the relative shape of the flowpath in the subsurface (fig. 14). Hydrogeologic sections crossing the western Medina flowpath at three locations are shown in figures 15a–c. These sections indicate the size and shape of the cross-sectional area that water moves through in the western Medina flowpath. A hydrogeologic section along a line following the western Medina flowpath is shown in figure 16. This section indicates that the Edwards aquifer is laterally continuous along the flowpath and that ground water might flow along the path without obstruction.

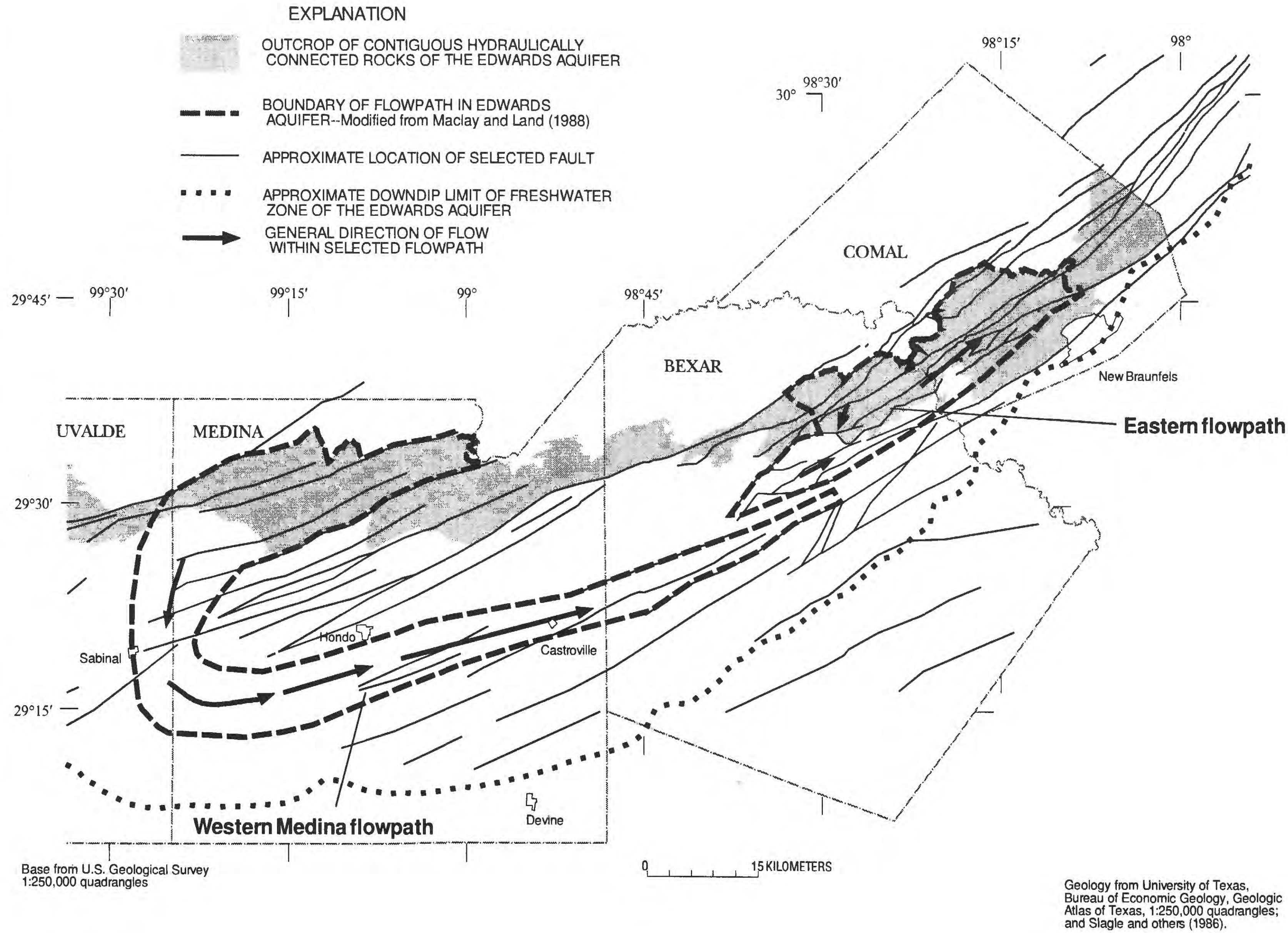


Figure 12. Locations of selected flowpaths of the Edwards aquifer, San Antonio region, Texas.

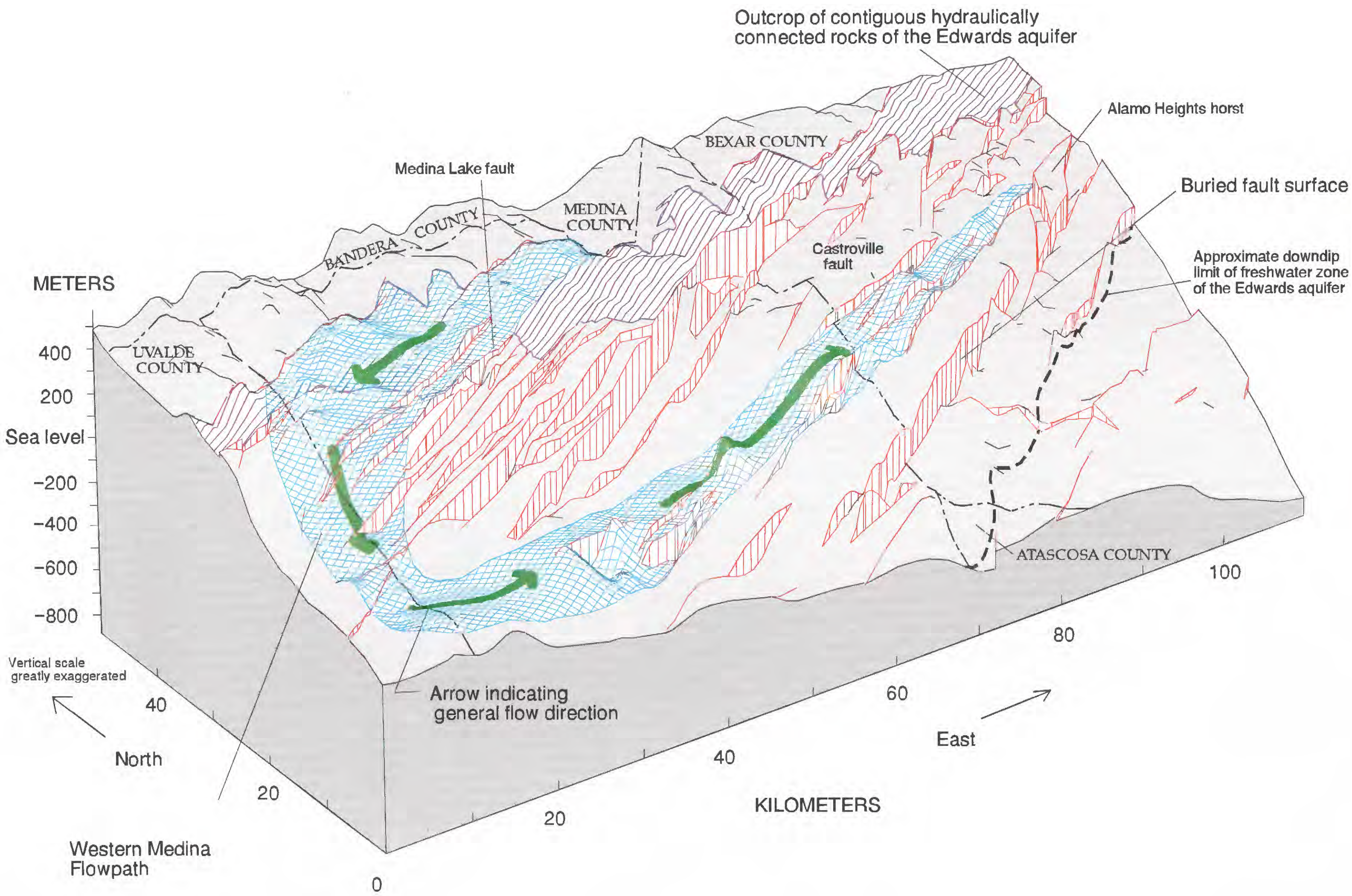


Figure 13. Conceptual model of the Edwards aquifer western Medina flowpath area and approximate flow directions, San Antonio region, Texas.

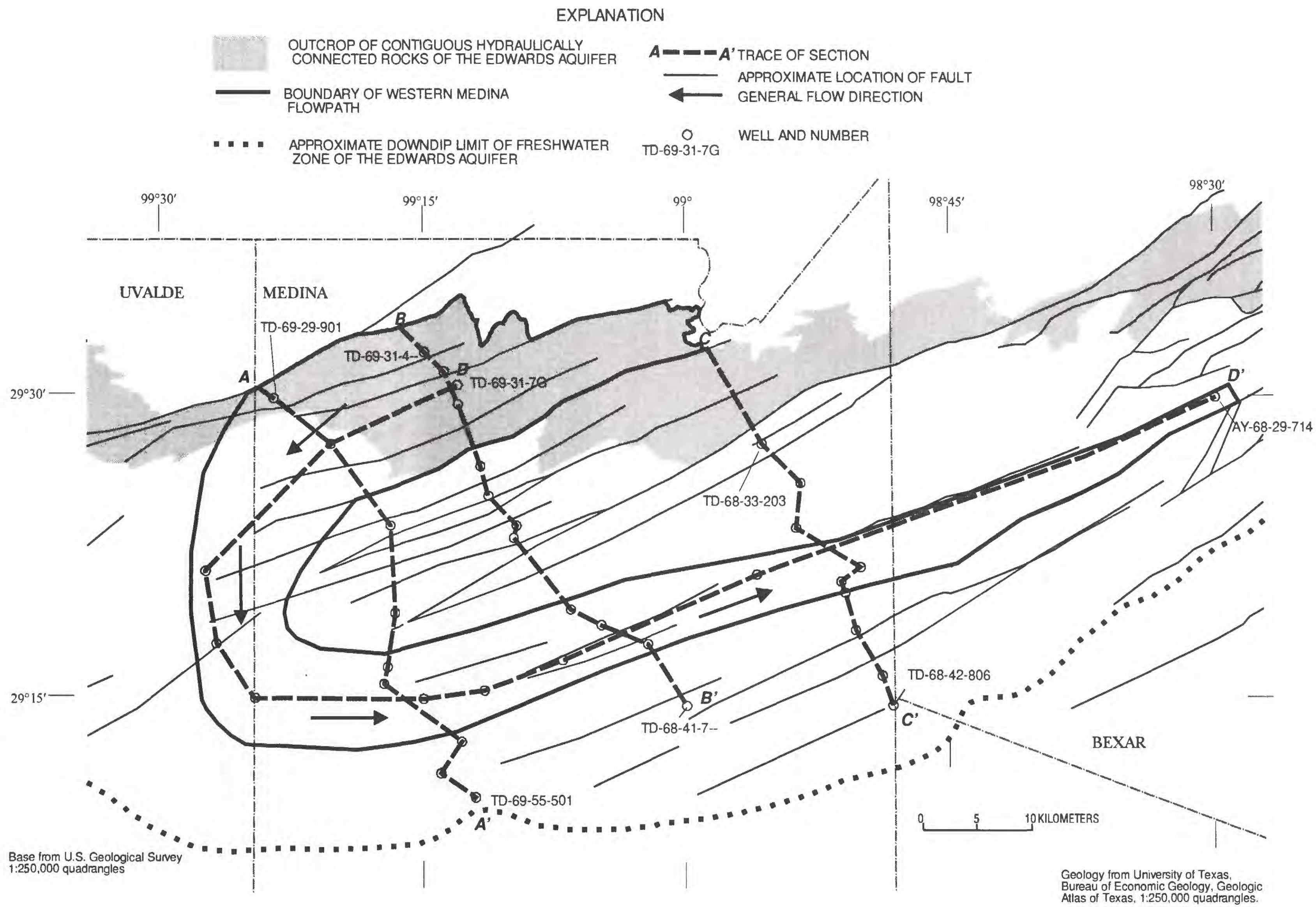


Figure 14. Locations of hydrogeologic sections across and along the Edwards aquifer western Medina flowpath, San Antonio region, Texas.

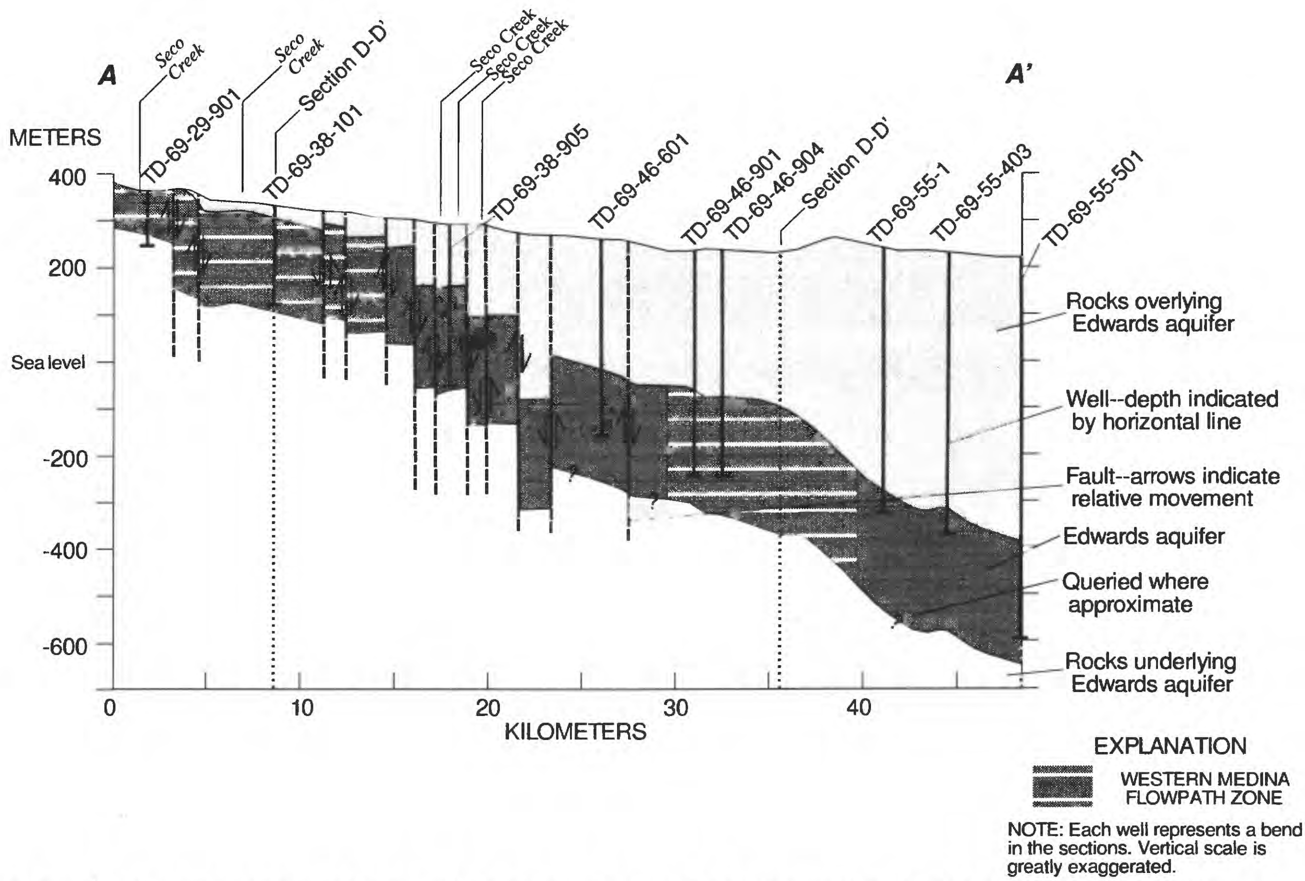


Figure 15a. Hydrogeologic section *A–A'* across the Edwards aquifer western Medina flowpath, San Antonio region, Texas.

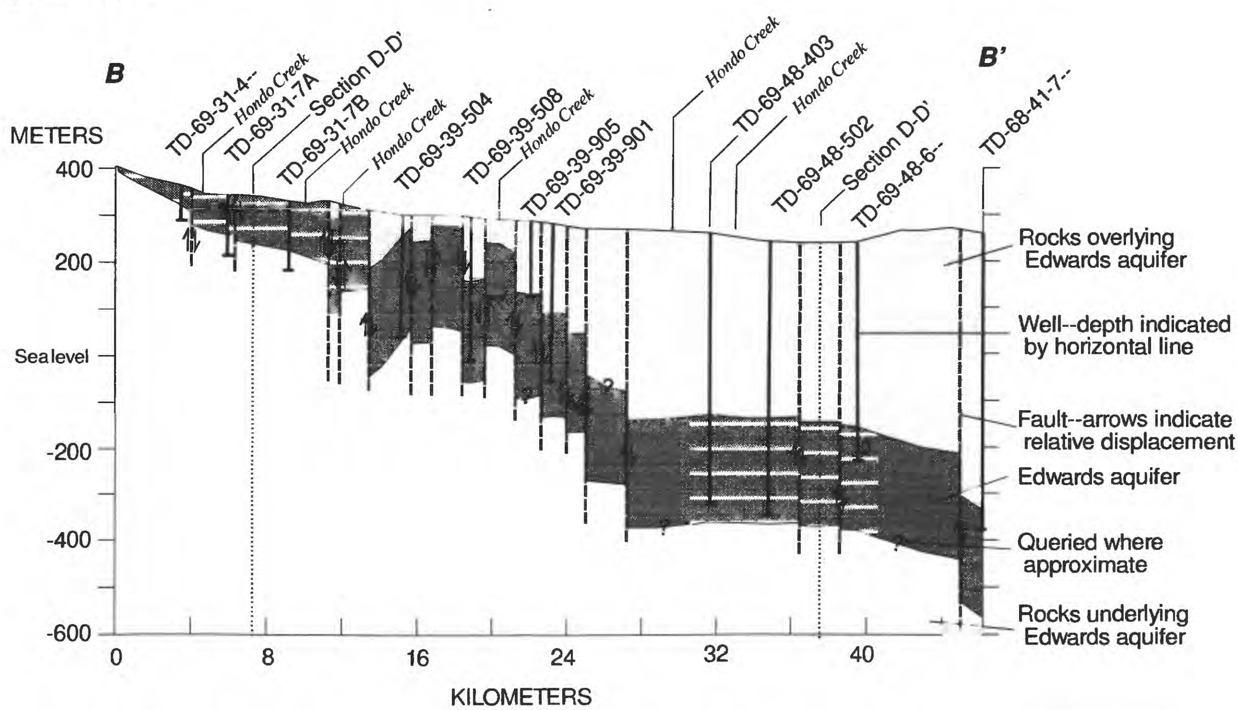


Figure 15b. Hydrogeologic section *B–B'* across the Edwards aquifer western Medina flowpath, San Antonio region, Texas.

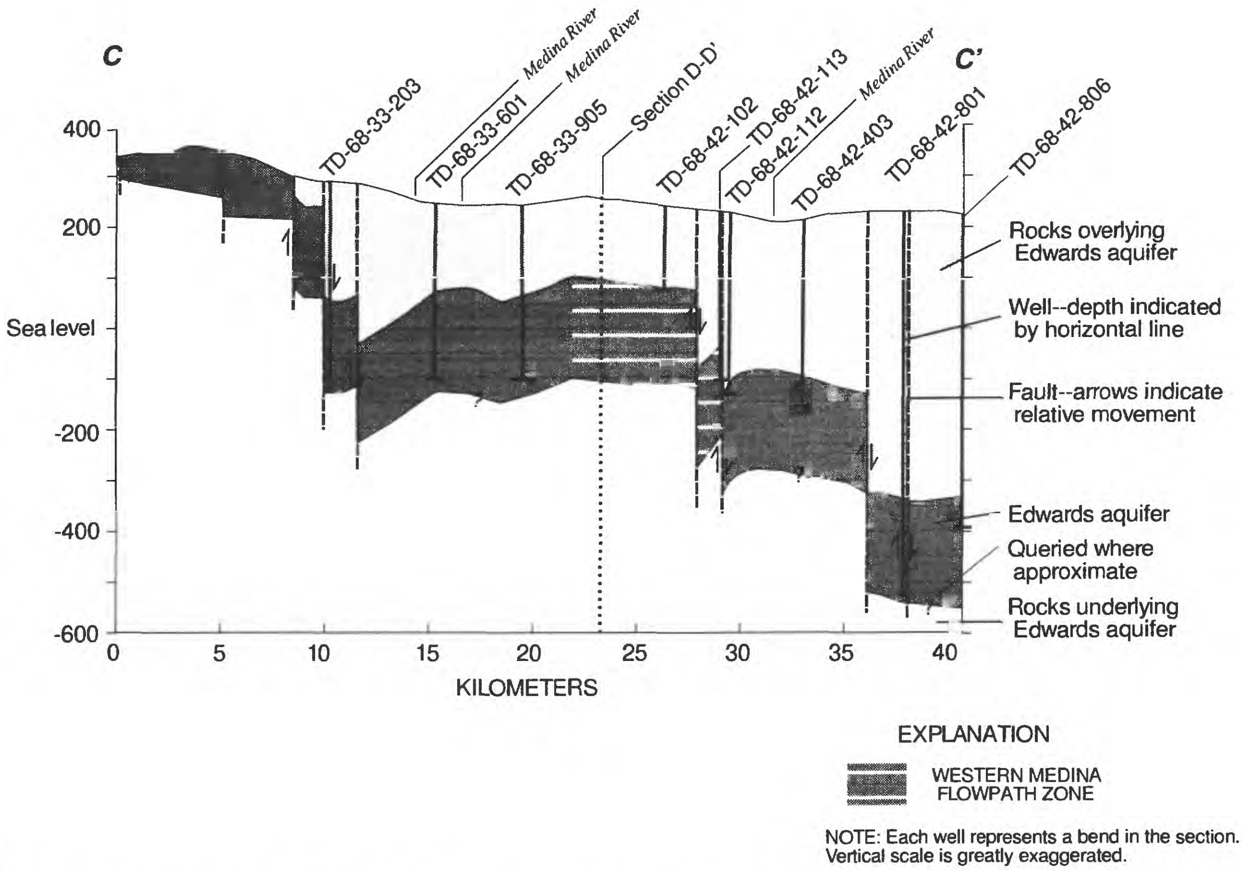


Figure 15c. Hydrogeologic section *C–C'* across the Edwards aquifer western Medina flowpath, San Antonio region, Texas.

Associated Recharge Area

The recharge area encompassed by the western Medina flowpath includes part of the Sabinal River Basin, all of the Seco Creek and Hondo Creek Basins, and a small section of the Medina Lake and Medina River Basins (fig. 9). Recharge from Medina Lake to the western Medina flowpath is assumed negligible for this analysis. The average annual recharge for the western Medina flowpath section of the Edwards aquifer is about 140 million m^3, about 17 percent of the average annual recharge during 1982–89 (Nalley and Thomas, 1990).

Water-Level Gradient

Holt (1959) reported a substantial number of Edwards aquifer wells in northern Medina County. Holt (1959) assumed that the faults were flow barriers and he interpreted the water-level measurements accordingly. The potentiometric surface drafted by Holt (1959) in September 1952 shows many discontinuities in the potentiometric surface at the faults. Discontinuities exist where identifiable displacement of the potentiometric surface is at a fault. Water-level measurements made in September 1952 are shown in figure 17. These water-level measurements are representative of steady-state or near steady-state conditions because the rate of well withdrawals was small during that period. Water-level measurements also were made during a dry period (July–August 1989) (fig. 18). These measurements are not steady state because of the large withdrawals from wells during this period.

Available water-level data are insufficient for determining an accurate potentiometric surface of the area for two reasons. First, the steepest gradient is always in or adjacent to the water-table zone; therefore, flow-barrier faults in that zone probably create the largest discontinuities in the potentiometric surface. Second, water levels were not measured in wells within all fault blocks. Extrapolation of water levels across

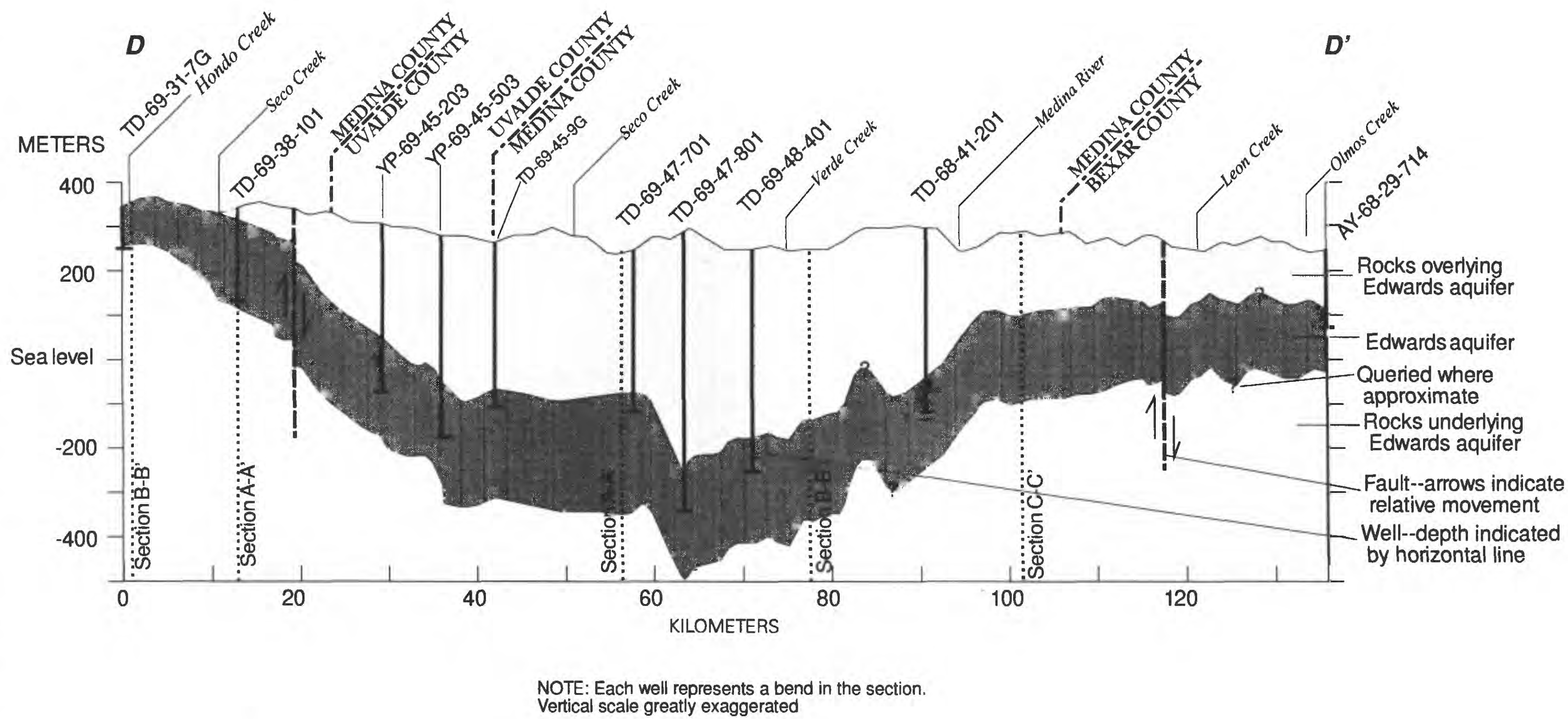


Figure 16. Hydrogeologic section *D–D'* along the Edwards aquifer western Medina flowpath, San Antonio region, Texas.

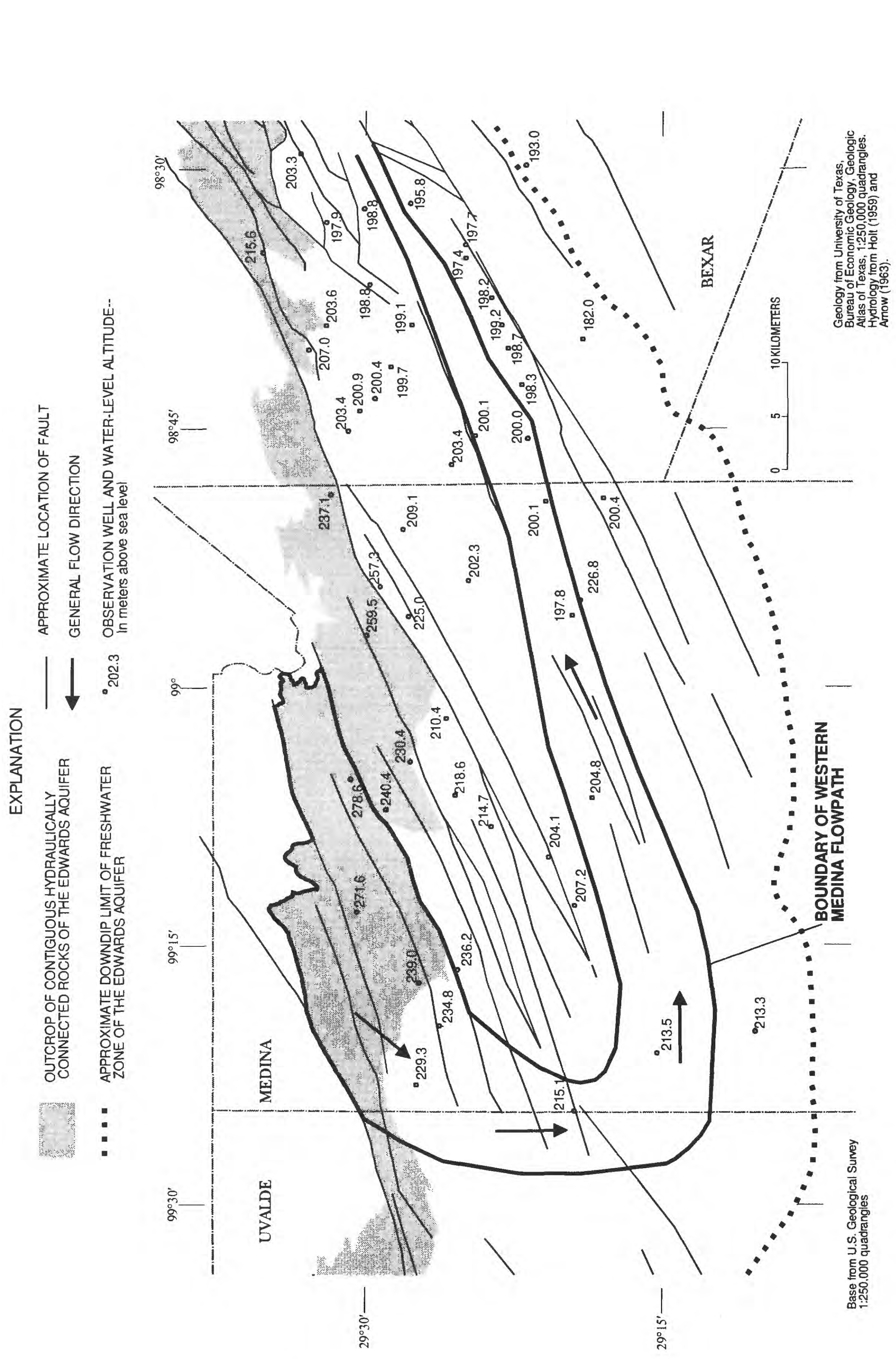


Figure 17. Water levels in observation wells in the Edwards aquifer western Medina flowpath area, San Antonio region, Texas, September 1952.

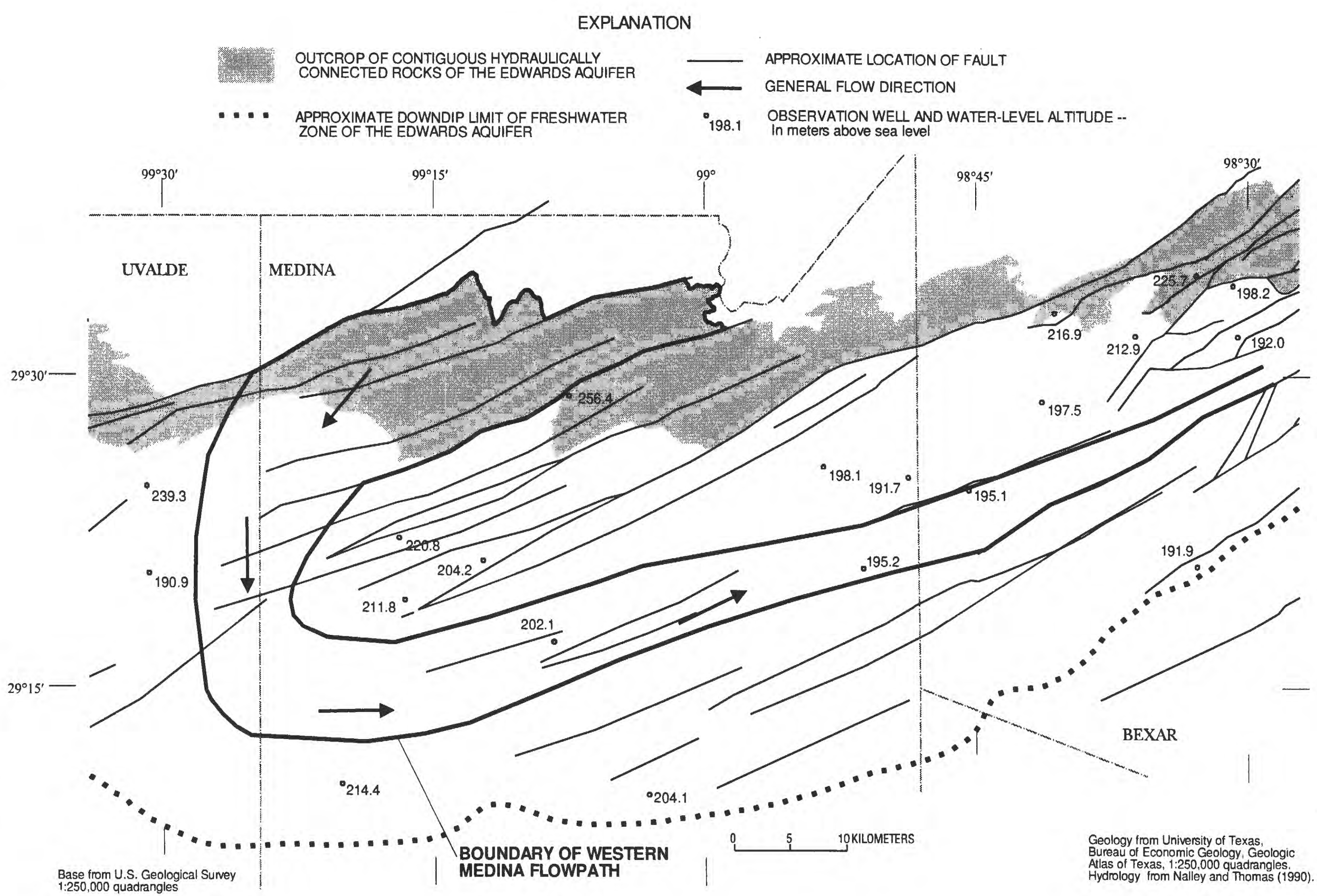


Figure 18. Water levels in observation wells in the Edwards aquifer western Medina flowpath area, San Antonio region, Texas, July–August 1989.

flow-barrier faults is unwarranted. The available data can only be interpreted for regional flow directions.

Mass water-level measurements of the Edwards aquifer wells probably are of limited value in interpreting well-to-well, water-level gradients. Maclay and others (1980) reported that water levels in some Bexar County wells vary daily from 0.6 to 1.5 m. The range of daily variation in a well greatly depends on the quantity of water withdrawn from it and nearby wells. The high transmissivity of the Edwards aquifer (920,000 m^2/d, Maclay and Land, 1988, p. 26) tends to spread the water-level decline over a wide area, thus creating a nearly flat but fluctuating potentiometric surface (Maclay and others, 1980, p. 21.). The area of highest transmissivity covers part of eastern Uvalde County, central and southern Medina County, central and southern Bexar County, and a narrow strip through Comal and Hays County (Maclay and Land, 1988).

Much of the western Medina flowpath is included in the area of highest transmissivity, particularly in the area where most water-level measurements were made in wells in the western Medina flowpath. The time of day when a water-level measurement is made has a substantial effect on the resultant water-level gradient computed toward nearby wells. Maclay and others (1980) concluded that other factors, such as air-pressure changes and solar or lunar tides, also have a substantial effect on water levels in many wells in the confined zone. These factors make interpretation of gradients among wells difficult, uncertain, and potentially misleading. Therefore, potentiometric-surface maps of the Edwards aquifer should be used only as an approximate, regional indication of flow direction even along a hypothesized flowpath.

Local heterogeneities in secondary porosity distribution caused by development of conduits or orientation of fractures might create local (less than 1 km^2) anisotropy. Caves in the subsurface Edwards aquifer might create anisotropic flow conditions; however, because the existence and location of these features in the confined zone and recharge area have not been determined, their effectiveness cannot be assessed. The available data are insufficient to determine if anisotropy occurs on a regional (tens to hundreds of square kilometers) scale. Faults with displacement of 50 percent or more of the aquifer thickness are lateral discontinuities (Freeze and Cherry, 1979) forming barriers that divert flow. Even if the apparent regional hydraulic gradient is normal to the faults, the flow of water will be parallel or sub-parallel to the flow-barrier faults. The disparity between the regional hydraulic gradient (northwest to southeast) and the movement of water in the aquifer (southwest and east or northeast) does not entail regional anisotropy in the Edwards aquifer.

Previous studies using numerical simulation of the ground-water flow in the Edwards aquifer included regional anisotropy as a variable to force the model to move water toward the major springs from the recharge area (Maclay and Land, 1988; Klemt and others, 1979). If the Edwards aquifer is isotropic on a regional scale with internal flow boundaries, then a network of more closely spaced observation wells would be necessary to map the water-level gradient within fault-bounded blocks for the accuracy needed to determine the movement of water along a specific flowpath.

Water-level measurements made in 1952 and 1989 indicate large variations among adjacent wells, almost as great as the regional gradient in some areas (figs. 17, 18). The variation is so great among the measured water levels that it is difficult to identify an overall trend (or gradient) in the area of the western Medina flowpath. These water-level variations might result from: (1) water-level measurements made in wells that actually tap two or more hydraulically isolated layers in the Edwards aquifer; (2) measurement error; (3) unsteady conditions at time of measurement; or (4) strong heterogeneities in the Edwards aquifer at a local scale (less than 1 km^2). To fully describe the daily variation in water levels in an area of high transmissivity, many closely spaced observation wells need to be measured in shorter intervals (less than 1 hour).

Geochemical Gradient

To test for temporal trends, major dissolved-ion concentrations in water samples collected from the Edwards aquifer during two periods (1968–75 and 1985–90) were compared (table 5). Another set of analytical data was examined for spatial trends along the flowpath. Thus, three related data subsets were compiled for each of the selected flowpaths. The first two subsets include data from well samples within and near each selected flowpath. The third data subset includes wells sampled within the selected flowpath only.

Wells with five or more water samples analyzed during 1968–90 (called the serial subset) were included in the analyses because fewer than five would compromise the validity of statistical tests. The mean sample concentrations for each well were compared among wells. The data are summarized for each

Table 5. Selected properties and constituents of water samples collected during 1968–75 and 1985–90 from the western Medina and eastern flowpaths in the Edwards aquifer, San Antonio region, Texas

[Specific conductance, microsiemens per centimeter at 25 degrees Celsius; temperature, degrees Celsius; all other units in milligrams per liter]

Property or constituent	1968–75				1985–90			
	No. of samples	Mean	Median	Standard deviation	No. of samples	Mean	Median	Standard deviation
			Western Medina flowpath					
Specific conductance	7	469	466	30	4	474	471	13
Temperature	6	24.3	23.8	2.2	4	22.8	22.4	1.1
Calcium, dissolved	7	69	69	7.8	4	75	73	6.6
Magnesium, dissolved	7	15	14	2.1	4	12	14	3.8
Sodium, dissolved	7	7.9	7.7	1.1	4	7.1	7.2	1.3
Alkalinity as $CaCO_3$	7	206	203	10	4	213	212	9.4
Sulfate, dissolved	7	18	18	3.0	4	14	16	3.0
Chloride, dissolved	7	14	13	2.8	4	12	11	4.8
			Eastern flowpath					
Specific conductance	33	539	537	27	20	587	568	109
Temperature	32	22.7	23.0	.7	20	23.0	23.0	.6
Calcium, dissolved	31	93	93	11	20	104	100	16
Magnesium, dissolved	31	12	11	5.3	20	9.9	11	4.5
Sodium, dissolved	24	6.0	5.4	2.9	20	11	7.0	11
Alkalinity as $CaCO_3$	31	266	266	18	20	283	270	46
Sulfate, dissolved	32	11.3	9.0	7.4	20	15	14	8.3
Chloride, dissolved	32	9.6	9.3	2.8	20	15	13	8.1

selected flowpath in tables 6 and 7. Similar data for the major springs representing the distal end of the eastern flowpath are summarized in table 8.

A subset of the interval data subsets was selected to determine the arithmetic means of all samples for each time subset of the interval data sets. These means were compared and used to determine saturation states of several minerals. A computer program (WATEQ4F) was used to compute dissolved species distribution and mineral saturation states (Ball and others, 1991). The water-sample analyses of the flowpath data set were used to determine mineral saturation states by WATEQ4F.

Dissolved Ions

Cowart (1980) traced the movement of dissolved uranium through the Edwards aquifer and concluded that little rock dissolution occurs in the Edwards aquifer between the recharge and discharge of freshwater. Analyses of the water samples taken from the two interval data sets in and around the western Medina flowpath indicated that, despite small variations in the major ions along the flowpath, no overall trend in water chemistry is indicated between the two time intervals. The locations of wells sampled periodically during 1968–90 for inorganic ions and during 1989–90 for volatile organic compounds are shown in figure 19.

Few accessible wells with reliable construction and geologic records are available in northern Medina County. Wells in the recharge area of the western Medina flowpath were not sampled during the past 20 years. The few wells that were sampled are near the boundary between the recharge area and the confined

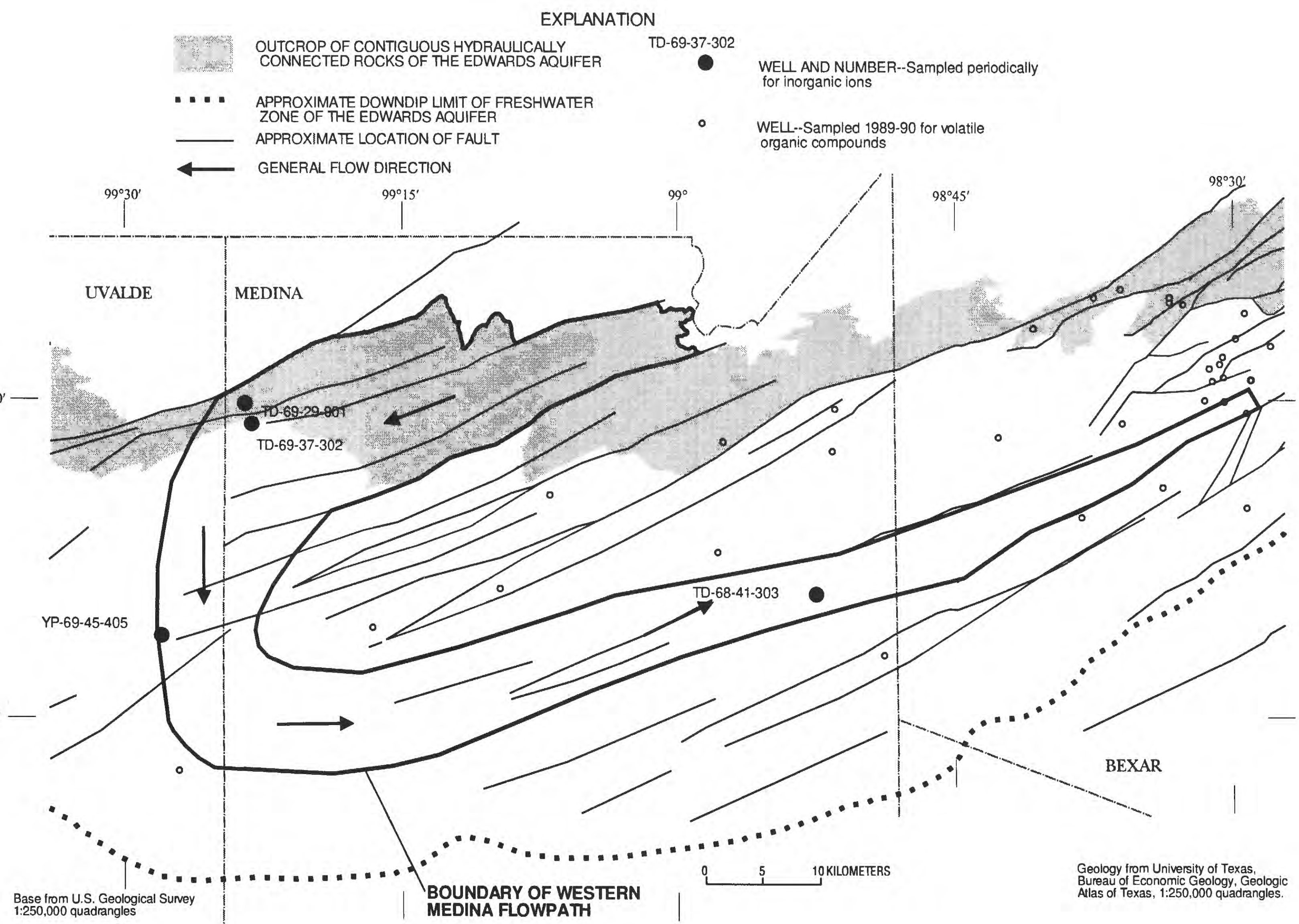


Figure 19. Locations of wells sampled periodically during 1968–90 for inorganic ions and wells sampled during 1989–90 for volatile organic compounds in the Edwards aquifer western Medina flowpath area, San Antonio region, Texas.

Table 6. Selected properties and constituents of water samples from four wells in the western Medina flowpath in the Edwards aquifer, San Antonio region, Texas

[Specific conductance, microsiemens per centimeter at 25 degrees Celsius; pH, standard units; nc, not calculated; temperature, degrees Celsius; all other units in milligrams per liter]

Property or constituent	No. of samples	Mean	Median	Standard deviation	Standard error of mean	Minimum	Maximum	First quartile	Third quartile
				TD–68–41–303 (1972–90)					
Specific conductance	19	480	480	10	5	440	500	470	490
pH	19	nc	7.2	nc	nc	6.7	7.6	nc	nc
Temperature	19	23.8	24.0	.3	.1	23.0	24.5	23.5	24.0
Calcium, dissolved	18	69	69	1.4	.3	66	71	68	70
Magnesium, dissolved	18	15	15	.7	.2	14	16	15	16
Sodium, dissolved	17	8.9	8.6	.7	.2	7.9	10	8.4	9.4
Potassium, dissolved	17	1.1	1.1	.1	0	.9	1.2	1.1	1.1
Alkalinity as $CaCO_3$	18	205	205	3.1	.7	200	210	204	206
Sulfate, dissolved	18	16	16	2.1	.5	13	23	16	17
Chloride, dissolved	19	19	19	1.6	.4	14	22	18	19
				TD–69–29–901 (1976–90)					
Specific conductance	7	490	460	60	20	450	610	460	480
pH	7	nc	7.1	nc	nc	6.9	7.4	nc	nc
Temperature	7	22.7	23.0	.7	.3	21.5	23.7	22.0	23.1
Calcium, dissolved	7	87	84	10	4.0	79	110	81	87
Magnesium, dissolved	7	7.3	7.0	1.3	.5	5.7	10	6.8	7.5
Sodium, dissolved	7	6.1	5.6	1.7	.7	4.7	10	5.4	5.9
Potassium, dissolved	7	.9	.9	.1	0	.7	1.1	.7	1.0
Alkalinity as $CaCO_3$	6	224	222	9.4	3.8	213	240	218	232
Sulfate, dissolved	7	13	13	3.9	1.5	7.2	19	10	16
Chloride, dissolved	7	15	8.7	17	6.3	7.7	53	7.8	12
				TD–69–37–302 (1975–90)					
Specific conductance	8	500	500	20	10	480	550	480	530
pH	8	nc	7.2	nc	nc	6.9	7.4	nc	nc
Temperature	8	23.0	22.8	1.4	.5	21.5	26.0	22.0	23.4
Calcium, dissolved	8	81	80	8.2	2.9	72	98	74	84
Magnesium, dissolved	8	13	14	1.6	.6	9.9	14	11	14
Sodium, dissolved	8	7.6	7.4	1.0	.3	6.6	9.3	6.8	8.5
Potassium, dissolved	8	1.1	1.1	.1	0	1.0	1.2	1.0	1.2
Alkalinity as $CaCO_3$	8	221	220	11	3.9	208	244	212	224
Sulfate, dissolved	8	20	21	3.5	1.2	16	26	16	23
Chloride, dissolved	8	12	12	1.9	.7	10	15	10	14
				YP–69–45–405 (1979–90)					
Specific conductance	8	480	480	10	4	460	490	480	490
pH	8	nc	7.2	nc	nc	7.0	7.4	nc	nc
Temperature	8	22.7	22.8	.3	.1	22.4	23.0	22.5	23.0
Calcium, dissolved	8	72	72	2.1	.7	67	74	71	73
Magnesium, dissolved	8	14	14	.5	.2	14	15	14	15
Sodium, dissolved	8	7.8	7.6	.6	.2	6.9	9.1	7.4	8.1
Potassium, dissolved	8	1.1	1.1	0	0	1.0	1.1	1.0	1.1
Alkalinity as $CaCO_3$	7	210	210	2.4	.9	206	213	210	213
Sulfate, dissolved	8	19	19	2.5	.9	16	23	16	21
Chloride, dissolved	8	13	13	.6	.2	12	14	13	14

Table 7. Selected properties and constituents of water samples from seven wells in the eastern flowpath in the Edwards aquifer, San Antonio region, Texas

[Specific conductance, microsiemens per centimeter at 25 degrees Celsius; pH, standard units; nc, not calculated; temperature, degrees Celsius; all other units in milligrams per liter]

Property or constituent	No. of samples	Mean	Median	Standard deviation	Standard error of mean	Minimum	Maximum	First quartile	Third quartile
				AY–68–28–903 (1968–90)					
Specific conductance	33	710	700	70	10	560	910	670	740
pH	32	nc	7.0	nc	nc	6.6	7.5	nc	nc
Temperature	33	22.0	22.0	.4	.1	21.2	23.0	21.7	22.4
Calcium, dissolved	23	115	110	13	2.6	91	140	110	120
Magnesium, dissolved	23	13	13	1.0	.2	11	14	12	13
Sodium, dissolved	22	22	21	7.1	1.5	5.4	38	18	25
Potassium, dissolved	22	1.7	1.6	.3	.1	1.2	2.5	1.5	1.8
Alkalinity as $CaCO_3$	28	322	320	32	6.0	258	399	304	334
Sulfate, dissolved	23	23	22	4.2	.9	15	34	21	26
Chloride, dissolved	23	24	23	5.4	1.1	14	35	21	26
				AY–68–29–109 (1973–90)					
Specific conductance	17	580	580	20	50	540	620	560	590
pH	15	nc	6.9	nc	nc	6.5	7.4	nc	nc
Temperature	17	23.0	23.0	.3	.1	22.5	23.5	23.0	23.1
Calcium, dissolved	14	101	100	6.0	1.6	88	110	98	102
Magnesium, dissolved	14	11	10	2.1	.5	9.9	17	10	11
Sodium, dissolved	14	8.0	8.0	1.3	.3	6.3	11	6.9	8.9
Potassium, dissolved	14	.8	.8	.1	0	.7	.9	.7	.8
Alkalinity as $CaCO_3$	15	279	279	8.1	2.1	270	295	271	287
Sulfate, dissolved	14	8.3	8.2	2.3	.6	2.0	11	7.2	10
Chloride, dissolved	14	15	14	2.8	.7	11	21	13	17
				AY–68–29–303 (1972–90)					
Specific conductance	17	520	520	30	10	460	560	490	550
pH	17	nc	6.9	nc	nc	6.7	7.5	nc	nc
Temperature	17	22.4	22.4	.4	.1	22.0	23.5	22.0	22.8
Calcium, dissolved	15	92	92	5.2	1.3	79	100	89	95
Magnesium, dissolved	15	9.1	8.9	1.8	.5	6.6	12	7.4	11
Sodium, dissolved	15	4.8	4.7	.4	.1	4.2	5.8	4.5	5.1
Potassium, dissolved	15	.9	.9	.3	.1	.7	1.8	.8	.9
Alkalinity as $CaCO_3$	16	246	253	27	6.8	200	276	220	270
Sulfate, dissolved	15	11	10	4.6	1.2	1.0	18	8.7	14
Chloride, dissolved	15	9.1	8.9	2.3	.6	5.5	15	7.8	9.7
				AY–68–29–401 (1968–90)					
Specific conductance	13	560	550	20	10	520	610	540	560
pH	12	nc	7.0	nc	nc	6.8	7.7	nc	nc
Temperature	13	23.5	23.5	.5	.1	23.0	24.8	23.2	23.5
Calcium, dissolved	12	91	88	8.8	2.5	78	110	85	99
Magnesium, dissolved	12	15	16	3.2	.9	8.9	20	12	17
Sodium, dissolved	12	6.8	6.4	1.0	.3	5.7	8.6	6.1	7.9
Potassium, dissolved	12	.8	.8	.1	0	.6	1.1	.8	.9
Alkalinity as $CaCO_3$	12	273	271	7.6	2.2	260	287	268	280
Sulfate, dissolved	12	10	9.6	3.8	1.1	6.6	21	7.6	11
Chloride, dissolved	12	12	11	2.7	.8	8.5	18	10	14

Table 7. Selected properties and constituents of water samples from seven wells in the eastern flowpath in the Edwards aquifer, San Antonio region, Texas—Continued

Property or constituent	No. of samples	Mean	Median	Standard deviation	Standard error of mean	Minimum	Maximum	First quartile	Third quartile
				AY–68–29–405 (1968–90)					
Specific conductance	10	610	610	30	10	570	660	590	640
pH	10	nc	7.0	nc	nc	6.8	7.6	nc	nc
Temperature	10	23.4	23.2	.7	.2	22.5	24.5	22.9	24.0
Calcium, dissolved	9	106	110	8.8	2.9	90	120	100	110
Magnesium, dissolved	9	11	11	.5	.2	9.9	11	10	11
Sodium, dissolved	9	10	10	.7	.2	8.6	11	9.8	10
Potassium, dissolved	9	1.5	1.5	.2	0	1.2	1.8	1.4	1.6
Alkalinity as $CaCO_3$	9	288	287	17	5.7	253	311	281	302
Sulfate, dissolved	9	15	15	2.1	.7	13	19	13	17
Chloride, dissolved	9	15	14	2.2	.8	12	20	14	16
				AY–68–29–503 (1968–90)					
Specific conductance	6	540	540	7	3	531	550	532	545
pH	6	nc	7.4	nc	nc	6.9	7.6	nc	nc
Temperature	5	22.9	23.0	.9	.4	21.5	24.0	22.2	23.5
Calcium, dissolved	6	96	96	3.0	1.2	90	98	94	98
Magnesium, dissolved	6	11	11	.5	.2	11	12	11	12
Sodium, dissolved	3	4.5	4.4	.1	.1	4.4	4.6	4.4	4.6
Potassium, dissolved	3	.8	.7	.2	.1	.7	1.0	.7	1.0
Alkalinity as $CaCO_3$	6	275	277	6.5	2.6	262	279	272	279
Sulfate, dissolved	6	5.0	4.8	.7	.3	4.4	6.1	4.4	5.7
Chloride, dissolved	6	7.1	7.1	.4	.2	6.6	7.6	6.8	7.4
				AY–68–30–102 (1971–90)					
Specific conductance	5	510	510	10	5	490	520	500	510
pH	5	nc	7.0	nc	nc	6.9	7.4	nc	nc
Temperature	5	22.4	22.5	.2	.1	22.0	22.5	22.2	22.5
Calcium, dissolved	5	91	90	2.3	1.0	88	94	89	93
Magnesium, dissolved	5	6.9	6.8	.7	.3	6.3	8.0	6.4	7.4
Sodium, dissolved	4	6.5	6.4	.4	.2	6.2	7.0	6.2	6.9
Potassium, dissolved	4	.9	.9	.1	0	.8	1.0	.8	1.0
Alkalinity as $CaCO_3$	5	219	223	8.8	3.9	208	230	210	226
Sulfate, dissolved	5	25	24	6.0	2.7	18	32	20	31
Chloride, dissolved	6	11	11	.8	.3	10	12	11	12

zone. These well samples were considered representative of recharge water chemistry.

A series of boxplots indicating summary statistics for specific conductance, dissolved calcium, dissolved magnesium, alkalinity, dissolved sulfate, and dissolved chloride for well samples is shown in figure 20. The data in the boxplots are presented from left (recharge area) to right (down along the western Medina flowpath) indicating relative positions along the flowpath. Boxplots of all the analyses for Comal Springs (1968–90) are shown to represent the water chemistry at the distal end of the flowpath.

Dissolved calcium and alkalinity concentrations decrease down the western Medina flowpath, while dissolved magnesium concentrations increase (fig. 20). Specific conductance remains about the same along the flowpath. Data from the two shallowest wells (TD–69–29–901 and TD–69–37–302) plot somewhat close together (fig. 20) and do not represent a progression away from the recharge area but rather similar points along two parallel flow lines down the path. The two

Table 8. Selected properties and constituents of water samples from three Edwards aquifer springs, San Antonio region, Texas

[Specific conductance, microsiemens per centimeter at 25 degrees Celsius; pH, standard units; nc, not calculated; temperature, degrees Celsius; all other units in milligrams per liter]

Property or constituent	No. of samples	Mean	Median	Standard deviation	Standard error of mean	Minimum	Maximum	First quartile	Third quartile
				Comal Springs (1968–90)					
Specific conductance	36	527	528	20	5	480	560	520	540
pH	36	nc	7.2	nc	nc	6.5	7.6	nc	nc
Temperature	33	23.4	23.5	.4	.1	23.0	24.5	23.0	23.5
Calcium, dissolved	29	79	79	1.9	.4	75	82	78	80
Magnesium, dissolved	29	16	16	.4	.1	15	17	16	16
Sodium, dissolved	25	9.0	9.2	.7	.1	7.6	10	8.4	9.5
Potassium, dissolved	25	1.4	1.4	.1	0	1.2	1.6	1.3	1.4
Alkalinity as $CaCO_3$	35	235	233	12.7	2.2	212	300	230	238
Sulfate, dissolved	34	24	23	2.8	.5	17	35	23	24
Chloride, dissolved	34	14	14	1.6	.3	11	19	13	15
				Hueco Springs (1968–90)					
Specific conductance	19	580	580	30	10	490	600	560	580
pH	18	nc	6.9	nc	nc	6.5	7.4	nc	nc
Temperature	18	21.5	21.5	.6	.1	20.0	22.5	21.0	22.0
Calcium, dissolved	19	96	97	6.4	1.5	80	110	93	100
Magnesium, dissolved	19	13	13	2.4	.6	9.3	18	11	15
Sodium, dissolved	18	7.5	7.6	.8	.2	5.2	9.0	7.2	8.1
Potassium, dissolved	18	1.3	1.3	.1	0	1.1	1.5	1.2	1.4
Alkalinity as $CaCO_3$	18	273	273	11.4	2.7	238	286	270	282
Sulfate, dissolved	19	15	15	3.4	.8	9.7	22	14	18
Chloride, dissolved	19	12	11	1.6	.4	9.7	16	11	13
				San Marcos Springs (1968–90)					
Specific conductance	24	570	580	20	5	510	610	570	580
pH	23	nc	7.1	nc	nc	6.5	7.6	nc	nc
Temperature	21	21.8	22.0	.4	.1	21.0	23.0	21.5	22.0
Calcium, dissolved	20	84	84	2.5	.6	79	90	82	86
Magnesium, dissolved	20	18	18	.8	.2	17	20	18	19
Sodium, dissolved	18	11	11	1.1	.2	9.2	13	10	11
Potassium, dissolved	18	1.6	1.5	.2	0	1.4	2.0	1.5	1.7
Alkalinity as $CaCO_3$	24	254	253	6.1	1.2	246	267	250	259
Sulfate, dissolved	24	24	24	2.2	.5	18	29	22	25
Chloride, dissolved	24	19	19	1.6	.3	16	22	17	20

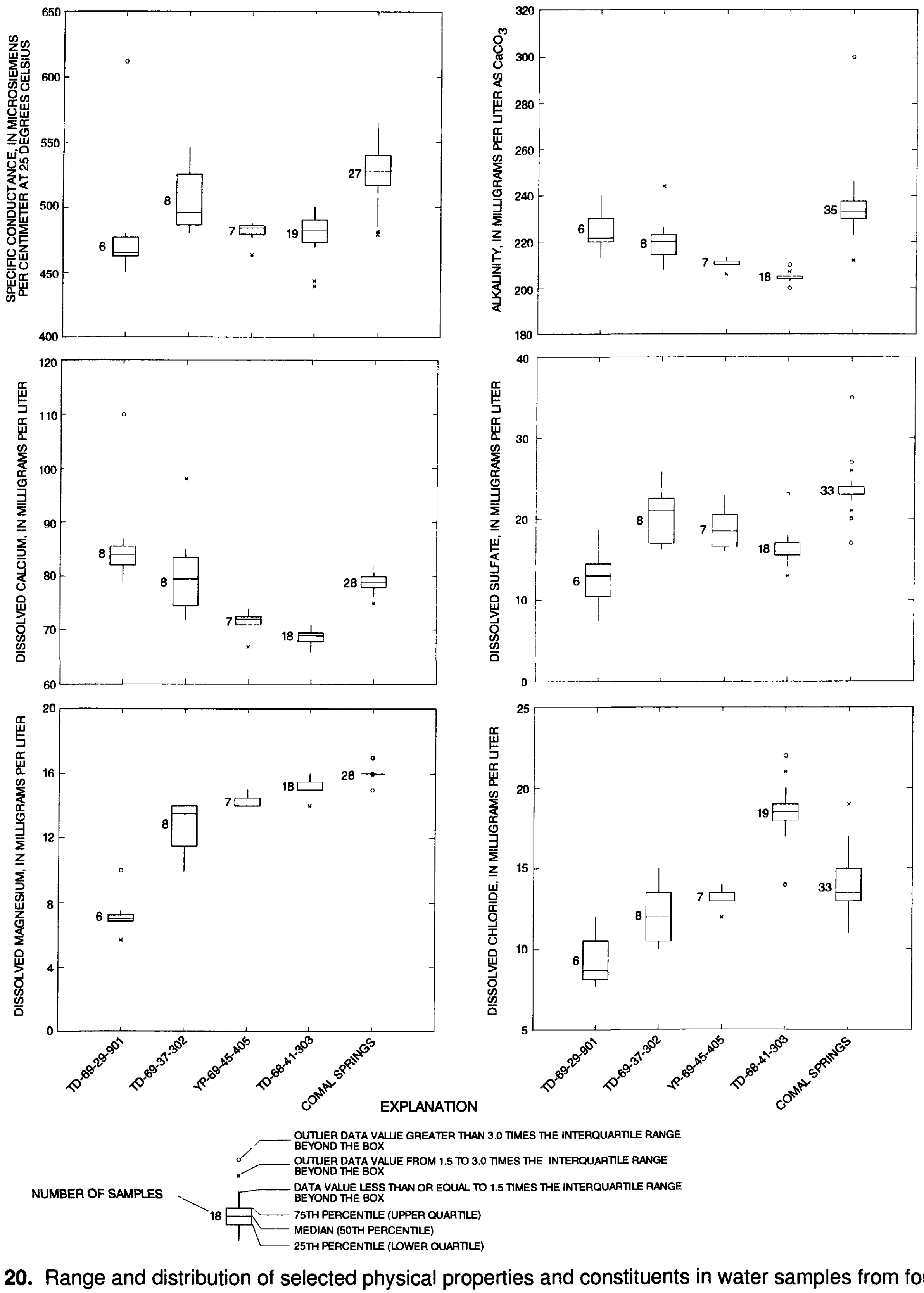


Figure 20. Range and distribution of selected physical properties and constituents in water samples from four wells in the Edwards aquifer western Medina flowpath area and from Comal Springs, San Antonio region, Texas, 1968–90.

Table 9. Saturation indices for calcite and dolomite average composition in water samples from selected wells in the western Medina and eastern flowpaths in the Edwards aquifer, San Antonio region, Texas

Well no.	No. of samples	Saturation index[1] for calcite	Saturation index[1] for dolomite
	Western Medina flowpath		
TD–69–29–901	7	-0.01	-0.79
TD–69–37–302	8	.10	-.27
YP–69–45–405	8	-.02	-.43
TD–68–41–303	19	-.04	-.40
	Eastern flowpath		
AY–68–28–903	23	.10	-.45
AY–68–29–109	14	-.07	-.76
AY–68–29–303	15	-.13	-.95
AY–68–29–401	12	-.01	-.48
AY–68–29–405	10	.05	-.57
AY–68–29–503	6	.35	.10
AY–68–30–102	5	-.12	-1.04

[1] Saturation index is defined as the logarithm of the ratio of activity product of ionic species to the equilibrium solubility constant for the selected mineral at a specific temperature. Because of uncertainty associated with the analyses, especially pH measurements, saturation for calcite ranges from -0.10 to 0.10 and for dolomite ranges from -0.20 to 0.20.

deepest or most distant wells—YP–69–45–405 and TD–68–41–303—show the smallest distribution of dissolved calcium, dissolved magnesium, and alkalinity concentrations. As water moves along the western Medina flowpath, the concentrations of these three ions might become more closely equilibrated with calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) as the geochemical environment becomes more stable and the temperature increases slightly. The saturation indices of the mean concentration data are listed in table 9. Calcite is at saturation concentration and dolomite is below saturation concentration for all sample means.

Dedolomitization is a process whereby calcite precipitates as magnesium dissolves. The hypothesis of dedolomitization contends that as dolomite dissolves, it releases calcium, magnesium, and bicarbonations; the increased amount of calcium and bicarbonate in solution causes the solution to become supersaturated with respect to calcium and, thus calcium precipitates. Dissolved magnesium would increase relative to dissolved calcium along the flowpath.

The dissolution of gypsum ($CaSO_4 \bullet 2H_2O$) or anhydrite ($CaSO_4$) is assumed to cause substantial amounts of dedolomitization in carbonate aquifers similar to the Edwards aquifer (Deike, 1990). A trend of decreasing dissolved sulfate for three of the wells (fig. 20) indicates that dissolution of gypsum or anhydrite probably is not involved in the presumed dedolomitization reaction. Rightmire and others (1974) and Rye and others (1981) determined that the sulfate in the Edwards aquifer freshwater zone entered the aquifer with the recharge water, and that the sulfate is from a distant gypsum rock source transported by wind from west Texas. Therefore, it is unlikely that gypsum or anhydrite dissolution is occurring, or that it drives the dedolomitization process in the freshwater zone.

Available data are insufficient to determine if the bulk chemical or mineralogical composition of the Edwards aquifer varies along the flowpath, and the water-chemistry data alone are not sufficient to confirm that dedolomitization occurs along the flowpath. The water-chemistry data also are not sufficient to confirm that water flows from the recharge area along the lines of these wells toward a distant discharge point.

Specific conductance is constant along the flowpath, and dissolved sulfate data indicate no consistent trend. The magnitude of the mass transfer between dolomite and calcite probably is so small that the dissolved uranium species studied by Cowart (1980) were not affected substantially. The data set for those wells sampled five or more times during 1968–90 also indicates no identifiable trend over time.

Tritium

Tritium is an unstable isotope of hydrogen created naturally in the earth's atmosphere and by atmospheric detonation of nuclear weapons. A tritium unit (TU) is 1 tritium atom per 10^{18} atoms of hydrogen. Only water samples with tritium concentrations below about 1 TU can be inferred to be only pre-1952 water; likewise, only tritium concentrations greater than 50 TU can be unequivocally inferred to be mostly or all post-1952 water (T.B. Coplen, U.S. Geological Survey, written commun., 1989). On the basis of water samples collected during 1967–71, Pearson and others (1975) concluded that little post-1952 water (high in tritium) had moved into the confined zone of the Edwards aquifer. Locations of sampled wells and tritium concentrations for 1975 and 1985 are shown in figure 21.

The tritium concentrations in water samples from wells completed in the recharge area of the western Medina flowpath are assumed to be similar to tritium concentrations in water samples from wells completed in the confined zone near the edge of the recharge area. However, the water from wells sampled in the recharge area has smaller tritium concentrations than would be expected if precipitation with high tritium concentrations had been contributing substantial quantities of water to the Edwards aquifer. Two factors possibly can explain why the tritium concentrations are low (fig. 21) even though hypothetically high tritium water has been recharging the aquifer since the early 1960s.

One factor that could cause the tritium concentrations in the recharge area to be smaller than expected stems from uncertainty about the storage capacity in the Edwards aquifer water-table zone. The porosity of the water-table zone could be much higher than previous studies indicated. Maclay and Rettman (1973) estimated an average specific yield or effective porosity of 0.031 (3.1 percent) for the water-table zone. Effective porosity is related to the quantity of water that can be yielded by the aquifer (storage capacity); however, total water-saturated porosity influences the tritium concentrations and dissolved substances in the aquifer. Recently, the University of Texas, Bureau of Economic Geology (1993) reported that total porosity of the Edwards aquifer is as high as 23 percent. If the quantity of water stored in the water-table zone is about seven times larger than previously thought, the volume-averaged tritium concentration would be about seven times smaller than expected, using the earlier, smaller estimate of storage.

Another factor that could affect the tritium concentrations in the recharge area is leakage of streamflow—base flow of streams draining the Trinity aquifer in the catchment area. Presumably this water has resided in the Trinity aquifer in the catchment area for weeks, months, or even years before being discharged at springs in the stream valleys. Depending on the portion of Edwards recharge water composed of base flow, this source of recharge might maintain a small tritium concentration in the Edwards recharge area.

Floodflow from the catchment area that leaks into the recharge area has been considered a substantial portion of Edwards aquifer recharge. Presumably, floodflow has a high tritium concentration similar to that of the precipitation that generated the stormflow. Pearson and others (1975) reported that base flow at the upper gage on the Nueces River prior to a rainstorm in August 1971 had a low tritium concentration, as would be expected for base flow that had spent many years in the Trinity aquifer. On the basis of data collected in Texas during the late 1960s and early 1970s, the precipitation had much higher tritium concentrations (Pearson and others, 1975). Overland runoff generated by the storm should have a tritium concentration similar to the precipitation. The small tritium concentration of water during the stormflow peak was similar to that of base flow before the storm. The peak tritium concentration in the streamwater flowed past the sample site while the streamflow was receding, about 7 days after the peak streamflow. On the basis of tritium concentrations in water samples collected during floodflow, the bulk of the water in the early part of the flood, including the peak floodflow, is rapidly increased ground-water discharge (through springs) and channel storage, rather than overland runoff. Because floodflow is a substantial component of recharge and because much of the water in a flood wave from the catchment area has small tritium concentrations, water in the Edwards aquifer recharge area would therefore have smaller tritium concentrations than would be expected if the flood wave were mostly precipitation-derived overland runoff. Without a thorough understanding of the basic hydrology of the recharge area and its relation to the catchment-area runoff, the extent of this effect on tritium concentrations in the water-table zone of the Edwards aquifer cannot be adequately assessed.

Tritium concentrations in water samples from the confined zone in the western Medina flowpath area were small, indicating that the water is mostly pre-1952. Relations between tritium concentrations in water

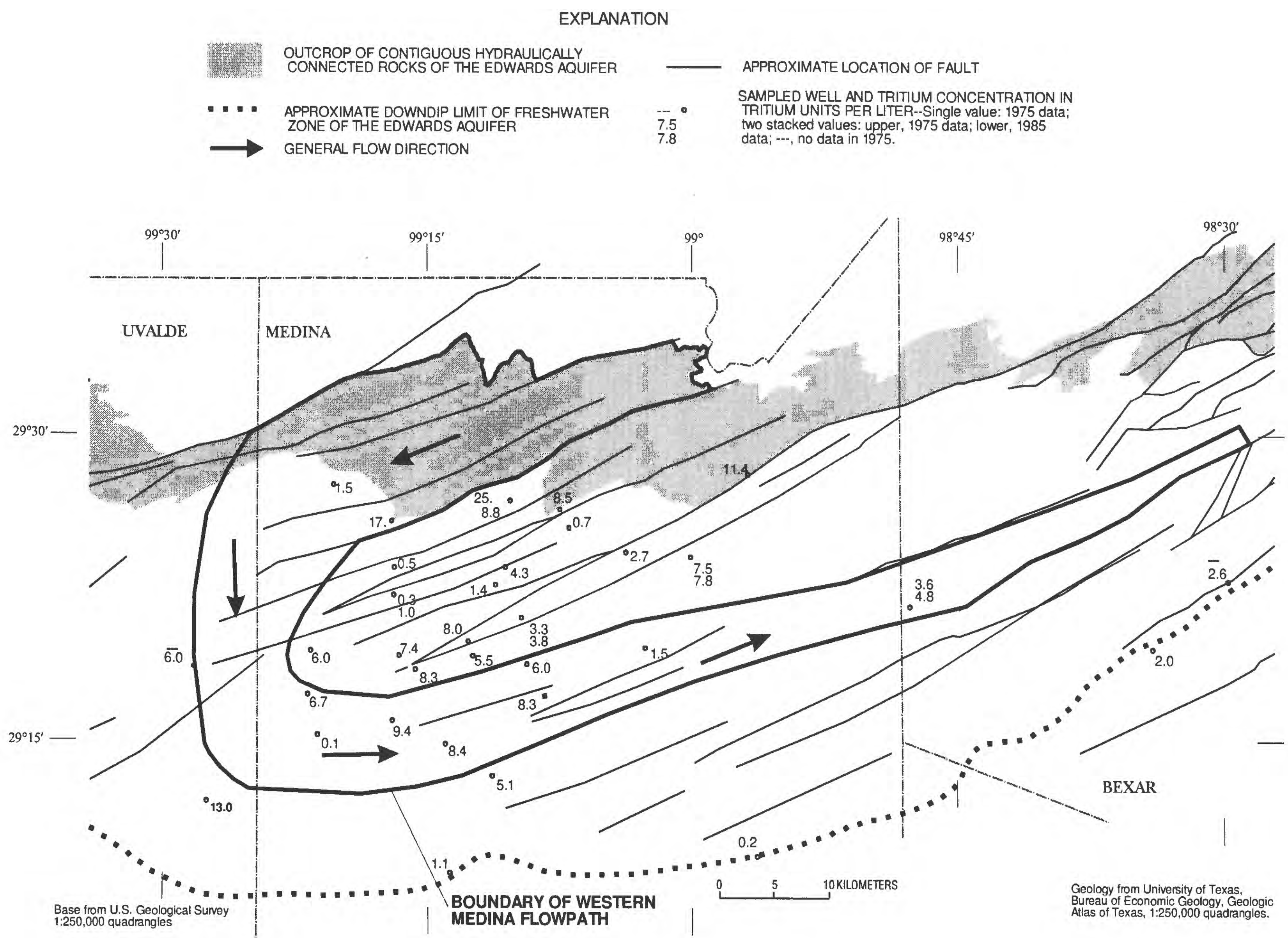


Figure 21. Locations of wells sampled for tritium concentrations in the Edwards aquifer western Medina flowpath area, San Antonio region, Texas, 1975 and 1985.

samples and six different aspects of well construction are shown in figure 22. The data used were from 22 wells in Medina County that had casing construction records, geologic information, and tritium data for 1975.

Land surface in Medina County generally slopes downward to the south or southeast. Wells near the recharge area generally have higher land-surface altitudes. The data in figure 22A indicate that as of 1975, high tritium water had not moved into any part of the confined zone. The altitude of the top of the Edwards aquifer also shows no correlation with tritium; however, the data cluster where the top of the Edwards aquifer is within 200 m of sea level. The land-surface altitude and the top of the Edwards aquifer slopes approximately in the same direction, with a steeper trend at the top of the aquifer.

The relation between tritium concentrations in water samples and depth from land surface to the top of the Edwards aquifer is shown in figure 22C. The Edwards aquifer in central and northern Medina County mostly comprises the Devils River Limestone, and the greatest effective porosity is near the top of the Edwards aquifer (Maclay and Small, 1984). If recharge flows faster near the top of the Edwards aquifer and if hydraulically isolated high permeability layers are present deeper in the aquifer, vertical stratification of tritium concentrations is possible. The data could indicate that either no wells actually tap a deeper, hydraulically isolated, permeable layer, or that no vertical stratification of tritium concentration occurs (fig. 22C). Most likely, none of the sampled wells are open to a regionally extensive deep permeable layer.

All but two wells tap a permeable layer near the top of the Edwards aquifer (fig. 22D). One well has the highest tritium concentration of all wells used in this analysis and the other has a small tritium concentration. Inferences cannot be drawn on the basis of only two data points with disparate tritium concentrations but similar distances below the top of the Edwards aquifer. The well with the highest tritium concentration is in or near the recharge area; it is the only well sampled that probably contained a substantial fraction of post-1952 water. All of the other wells tap water that might have no or only small (less than about one–fourth) volumes of post-1952 water. The data in figure 22E indicate no relation between tritium concentrations and depth from land surface to the bottom of open interval. The similarity between figures 22C and 22E indicates that tritium concentrations are not related to aquifer depth.

The relation between tritium concentrations in water samples and the length of the open interval is shown in figure 22F. Because wells with long open intervals probably would tap deeper permeable layers or multiple permeable layers, stratification of tritium concentration should be indicated. However, no correlation is indicated between the length of open interval and tritium concentrations in water samples.

Tritium data for 1985 are insufficient to determine if the pulse of high tritium water is in transit from the recharge to the discharge areas or has moved through the Edwards aquifer. As of 1985, the data do not indicate that a substantial quantity of high tritium water had moved into the western Medina flowpath.

Stable Isotopes

Several naturally occurring stable isotopes of hydrogen and oxygen exist in the terrestrial hydrosphere (Gat, 1980). Deuterium is hydrogen with an extra neutron and oxygen-18 has two more neutrons than the most abundant isotope, oxygen-16. Both isotopes, deuterium and oxygen-18, are stable and exist in small but measurable quantities in water molecules. The ratio of these stable isotopes to the isotopes that form the bulk of either element depends on the fractionating effect of physical processes under normal earth-surface conditions. Much information can be obtained from determining the small relative differences in distribution (or ratio of one isotope to the other) and the differential effects between the two sets of isotopes (Gat, 1980).

Dansgaard (1964) and Yurtsever (1975) determined that the isotopic fractionation of meteoric water follows several general empirical principles based on the theory of isotopic fractionation. Atmospheric water tends to become isotopically lighter as the containing air mass moves inland and precipitation condenses. Evaporation tends to increase the amount of the heavier isotope in the residual water. Isotopic ratios are determined more readily than the absolute concentration of the isotope in question (Gat, 1980). The ratios for hydrogen and oxygen are zero in Standard Mean Ocean Water (Craig, 1961).

Water samples were collected during 1988–90 for analyses of del deuterium (δD) and del oxygen–18 ($\delta^{18}O$). Most of the 12 wells and 3 lakes sampled for stable-isotopic analyses were in the eastern flowpath area northeast of the western Medina flowpath. Medina Lake and two other lakes in the study area were sampled

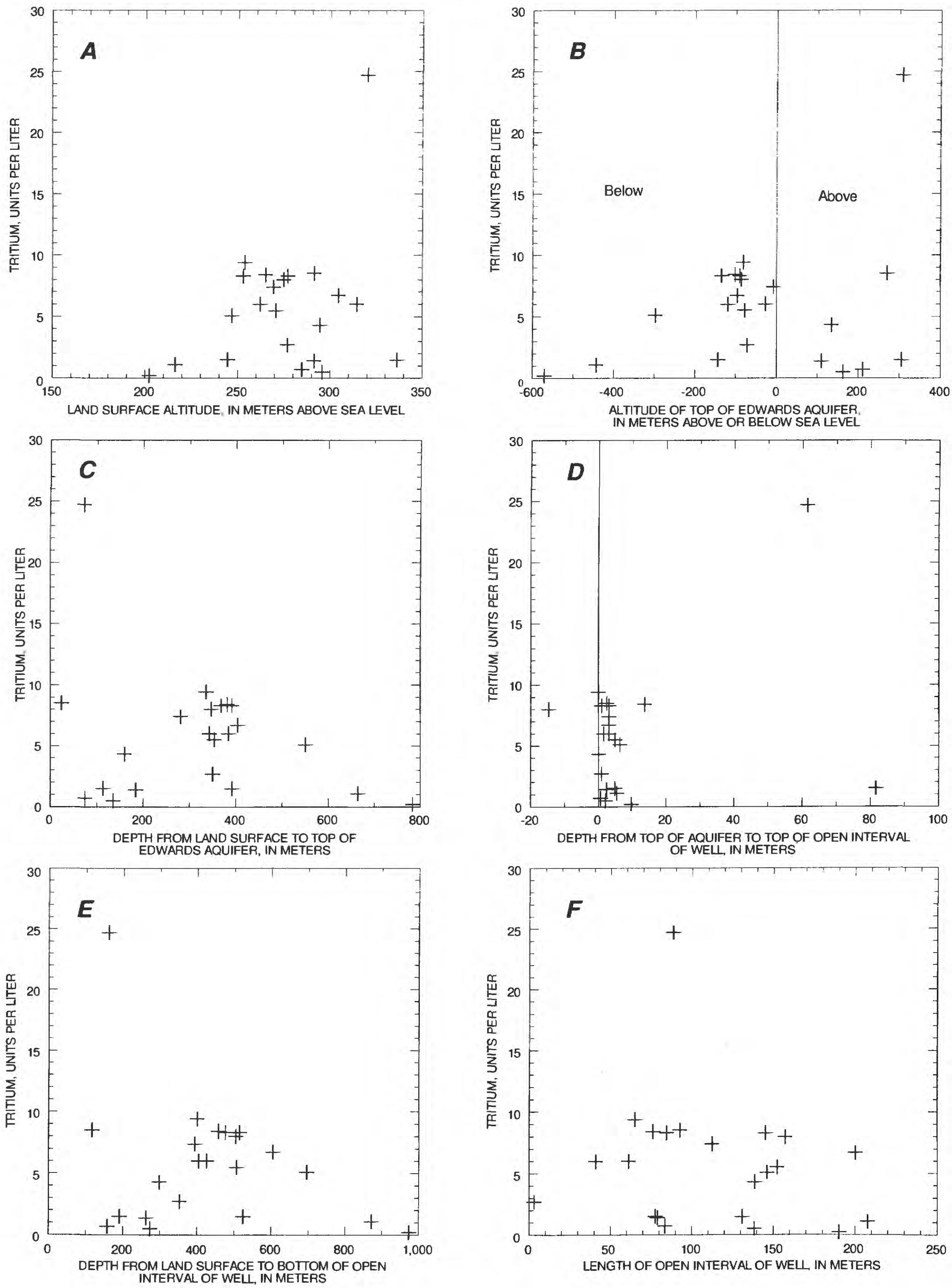


Figure 22. Relation of tritium concentrations in water samples from the Edwards aquifer and selected site and well-construction characteristics of sampled wells in Medina County, San Antonio region, Texas, 1975.

to determine the relative amount of isotopic fractionation that resulted from evaporation and potentially to help trace water movement in the Edwards aquifer. Tracing could involve either tracking water recharging the Edwards aquifer directly from Medina Lake or using lake water to inject as a tracer if the difference in stable-isotopic ratios between ground water and lake water was sufficiently great.

The ratio of stable-isotopic data from wells in the western Medina flowpath area is generally uniform and indicate that most of the freshwater in the Edwards aquifer is meteoric (derived directly from precipitation) with no substantial fractionation by evaporation. The mean stable-isotopic ratios for 79 ground-water samples, including water samples analyzed since 1968 (Pearson and Rettman, 1976) from the Edwards aquifer, are -25.7 (standard deviation 2.6) per mil δD and 4.3 (standard deviation 0.24) per mil $\delta^{18}O$. These values are assumed to represent the natural ratios of meteoric water in the study area.

The locations of two wells and one site in Medina Lake sampled for stable-isotopic ratios of hydrogen and oxygen are shown in figure 23. The stable-isotopic ratios in water samples from the two wells and one lake site are distinctly different from the mean for Edwards aquifer. The ratios from Medina Lake indicate that the lake has been subjected to substantial evaporation. The ratios for water samples from the two wells are different from the mean for the Edwards aquifer because the water samples are a mixture of recharge resulting from lake leakage and ambient recharge. The relative quantities of the two types of water can be estimated assuming that the ratios in the lake, when sampled, were uniform and represented a steady-state average for water leaking from the lake and that Edwards aquifer water generally has -25.7 per mil δD and -4.3 per mil $\delta^{18}O$.

Volatile Organic Compounds

Concentrations of trichlorofluoromethane (CCl_3F) in water samples from wells in northern Medina County and most of the western Medina flowpath area indicate that recharge entering the Edwards aquifer in the western Medina flowpath is not contaminated by the effects of land use (fig. 24). Small trichlorofluoromethane concentrations detected in water samples collected in Medina County (Randall and others, 1977) were caused by atmospheric trichlorofluoromethane concentrations (Thompson and Hayes, 1979) or by laboratory background concentrations and do not indicate contamination from land uses.

The analytical method can detect concentrations of several volatile organic compounds at levels well below concentrations of regulatory concern. The concentrations of all volatile organic compounds analyzed were below the background concentration and(or) detection limit in samples from Medina and Uvalde Counties.

The plume of freshwater recharge along the western Medina flowpath extends to north-central Bexar County (fig. 24). The flowpath of freshwater cannot be traced past the Alamo Heights horst because of: (1) occasional recharge at San Antonio and(or) San Pedro Springs; (2) local recharge of the Edwards aquifer in Bexar County; and (3) density and withdrawal rate of large-capacity public water-supply wells in central Bexar County. San Antonio Springs and possibly San Pedro Springs occasionally reverse flow direction and recharge the Edwards aquifer in the center of the freshwater confined zone under San Antonio (Veni, 1985). Isolating the recharge of atmospherically or land-use contaminated water in the area of San Antonio and San Pedro Springs from the pristine water flowing from the west might not be possible. The large volumes of ground water withdrawn in central Bexar County superimpose short-term, but relatively steep local gradients and thus local transient flowpaths on top of the natural regional flowpath, thereby dispersing the plume of freshwater. Therefore, tracing the flow of ground water from the center of Bexar County to Comal and San Marcos Springs probably is not possible.

Eastern Flowpath

The eastern flowpath (fig. 12) was selected because parts of the Edwards aquifer recharge area are becoming increasingly developed for residential and commercial uses. This development has caused concern about possible contamination of the Edwards aquifer in central Bexar County where many public water-supply wells are located.

Location and Geometry

The eastern flowpath lies almost entirely within the recharge area in northern Bexar County and in central Comal County. The eastern flowpath area (fig. 25) comprises the eastern flow and storage unit of Maclay and Land (1988). However, the ground-water divides Maclay and Land (1988) used in the recharge area in

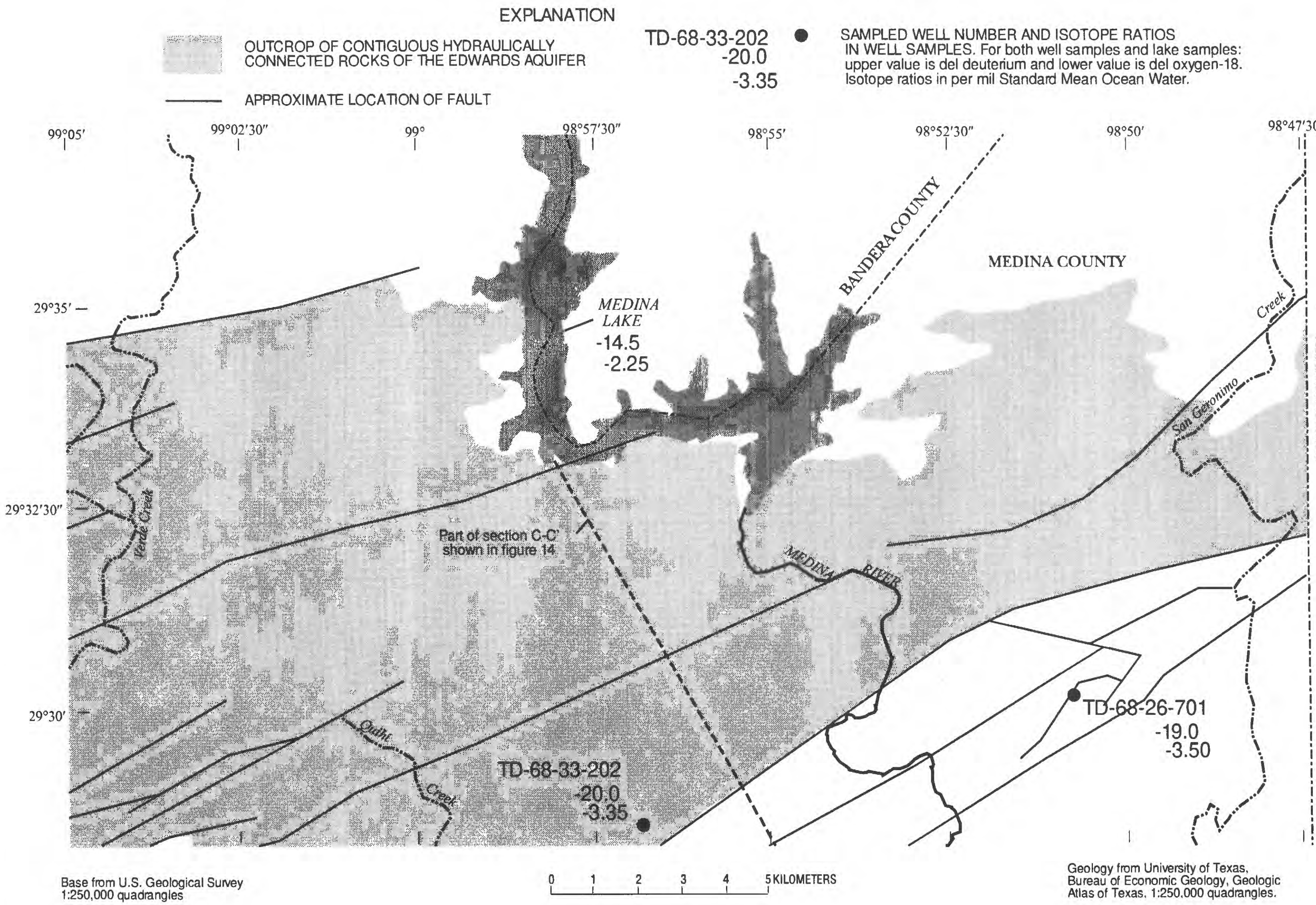


Figure 23. Locations of two wells completed in the Edwards aquifer and one site in Medina Lake sampled for stable-isotopic ratios of hydrogen and oxygen, San Antonio region, Texas, 1989–90.

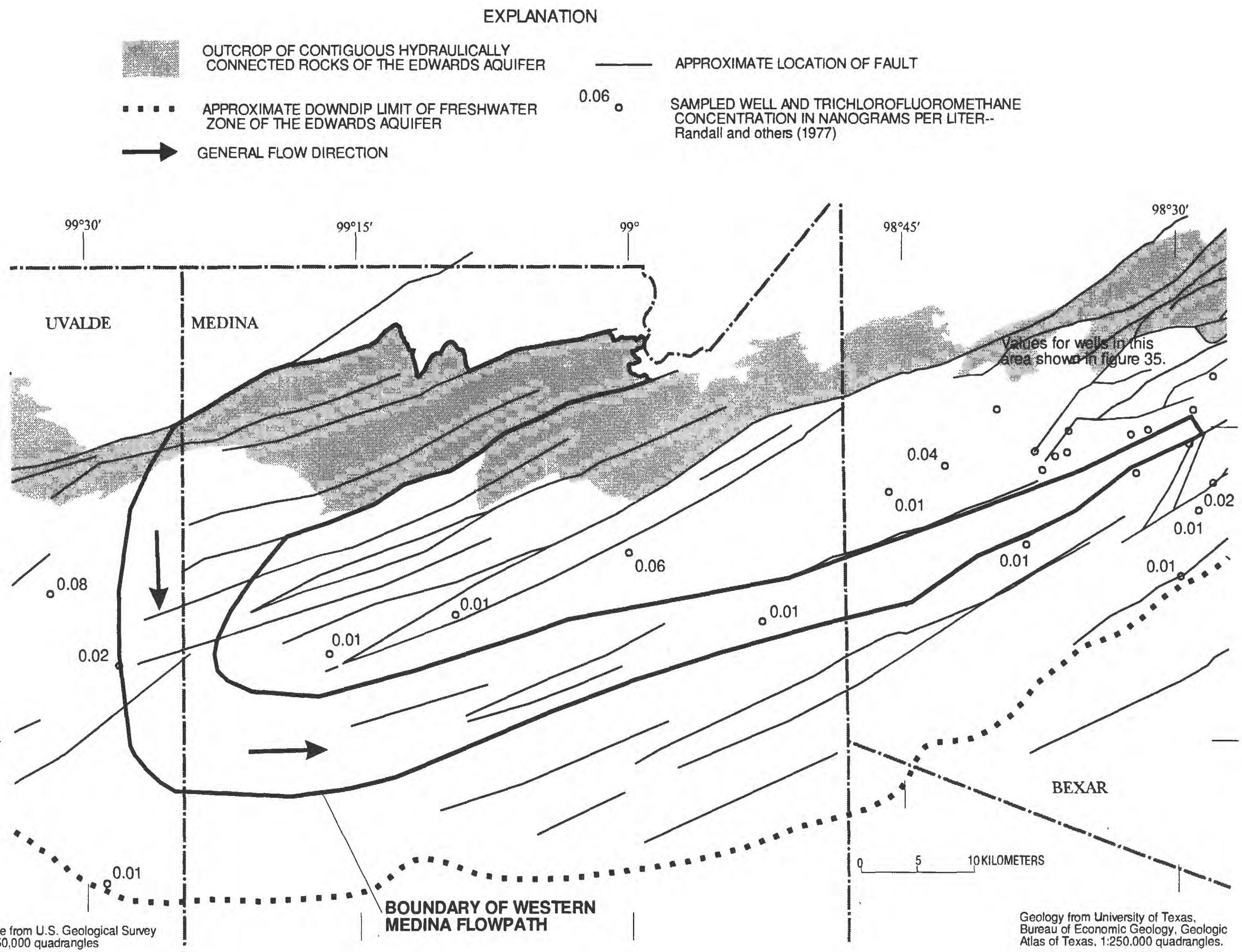


Figure 24. Locations of wells sampled for trichlorofluoromethane concentrations in the Edwards aquifer western Medina flowpath area, San Antonio region, Texas, 1977.

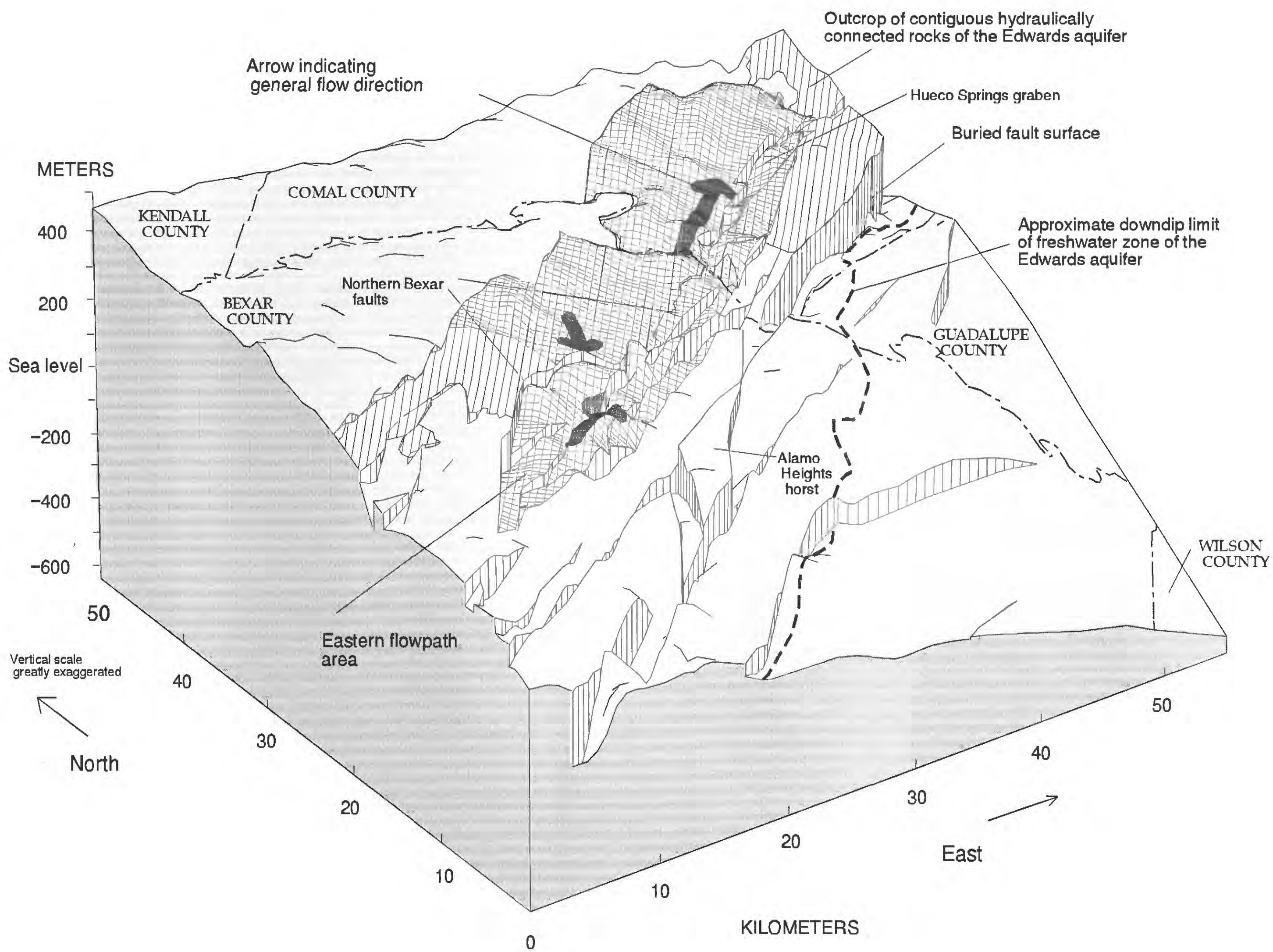


Figure 25. Conceptual model of the Edwards aquifer eastern flowpath area and approximate flow directions, San Antonio region, Texas.

north-central Bexar County and at the Guadalupe River valley in Comal County were only approximations.

The primary physical structures associated with the eastern flowpath include: (1) a series of faults along or near the southern edge of the outcrop area in Bexar County called Northern Bexar faults (fig. 25) by Maclay and Land (1988); (2) the shape of the recharge area; and (3) the series of faults that form a narrow zone called Hueco Springs graben by Maclay and Land (1988), where the rocks of the upper confining unit and other formations crop out between Cibolo Creek and the Guadalupe River valley (fig. 9) within the recharge area in Comal County.

Water-level measurements made during 1934, 1952, and 1989 indicate a ground-water divide in north-central Bexar County, although the exact location of the ground-water divide is undetermined. The divide might be ephemeral depending on the quantity of water in storage in the unconfined zone in Bexar County. The boundary along the Guadalupe River in the recharge area is inferred primarily because the river has incised deeply into and, in places, through the rocks of the Edwards aquifer. The Guadalupe River does not contribute any substantial net recharge to the Edwards aquifer (Puente, 1978).

The Edwards aquifer rocks are completely eroded in the Guadalupe River valley, except for a narrow strip of rocks (about 2 to 3 km wide) just north of New Braunfels (University of Texas, Bureau of Economic Geology, 1984). The strip of rocks probably is less than 100 m thick and is most likely unsaturated and, thus incapable of allowing substantial quantities of water to flow to or from sections of the Edwards aquifer north and east of the Guadalupe River. Therefore, water flowing in the Edwards aquifer to or from north of the Guadalupe River must flow through the narrow confined zone just northeast of New Braunfels (fig. 1). Maclay and Land (1988, p. A44) referred to this subsurface flow channel as the Gruene spillover. For this report, the eastern flowpath is cut off at the Gruene spillover because it would be difficult, on the basis of available data, to distinguish between locally derived recharge from north of the Guadalupe River and underflow in the Edwards aquifer flowing toward San Marcos Springs.

Hydrogeologic sections of the subsurface in and adjacent to the eastern flowpath show the geometry of the Edwards aquifer in the eastern flowpath and the relative shape of the flowpath in the subsurface (fig. 26). Hydrogeologic sections crossing the eastern flowpath at three locations are shown in figures 27a–c. These sections indicate the size and shape of the cross-sectional area that water moves through in the eastern flowpath. A hydrogeologic section along a line down the eastern flowpath is shown in figure 28. This hydrogeologic section indicates that the Edwards aquifer is continuous along the flowpath and ground water is able to follow the path without obstruction.

Associated Recharge Area

The recharge area encompassed by the eastern flowpath includes most of the area drained by Salado Creek, all of the Cibolo Creek Basin, and all of the East and West Prongs of Dry Comal Creek Basin (fig. 9). Estimating recharge for the eastern flowpath is much less certain than for the western Medina flowpath because these basins are not instrumented sufficiently to use the water-budget recharge method as outlined for the Nueces-West Nueces River Basin (Puente, 1978). However, the average recharge for the eastern flowpath is similar to the western Medina flowpath—about 17 percent of the average annual recharge for 1982–89 (Nalley and Thomas, 1990).

Several different and somewhat conflicting directions of regional flow are shown in figure 25. The simulated flow vectors of Maclay and Land (1988, p. 35) indicate even more directions of local flow within the eastern flowpath area.

Most karst features, including significant recharge features, are related to specific strata within the formations that constitute the Edwards aquifer. Stein and Ozuna (1995) identified maximum solution-related porosity in the leached and collapsed members of the Person Formation and in the grainstone and Kirschberg evaporite members of the Kainer Formation (fig. 29). These patterns of dissolution are the same as those reported by Maclay and Small (1984) for the confined zone of the Edwards aquifer and, to a lesser extent, by Rose (1972) in the saline-water zone downdip from the freshwater zone.

Fractures and dissolution openings allow for recharge to move down to the water table. Stein and Ozuna (1995) reported that the horizontal movement of water in and from the recharge area probably is similar to the stratified horizontal movement of water in the confined zone described by Maclay and Small (1984) because the two zones have similar overall porosity development. This is an important factor because the ability of faults with large displacement to divert flow results from the combination of stratified horizontal

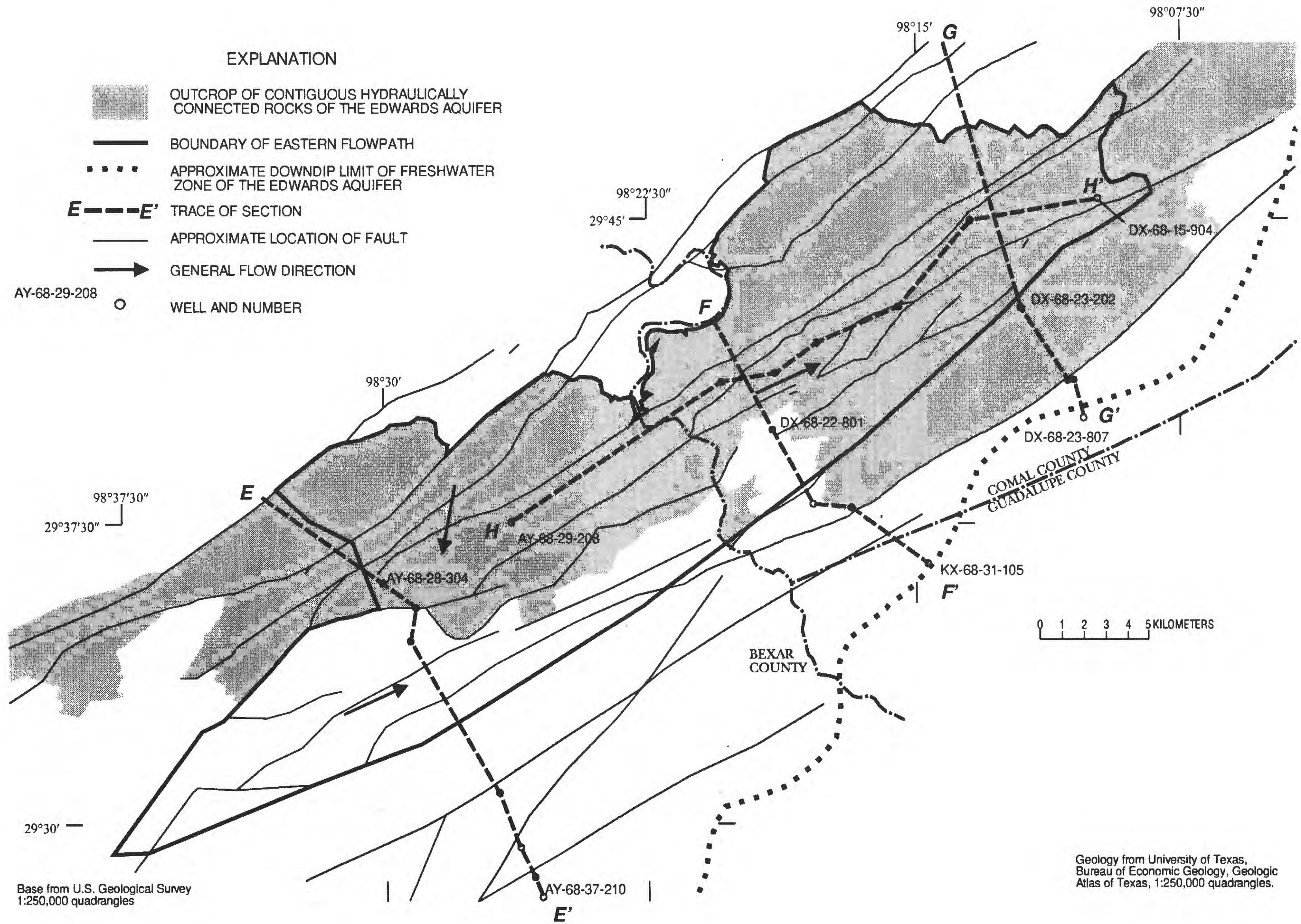


Figure 26. Locations of hydrogeologic sections across and along the Edwards aquifer eastern flowpath, San Antonio region, Texas.

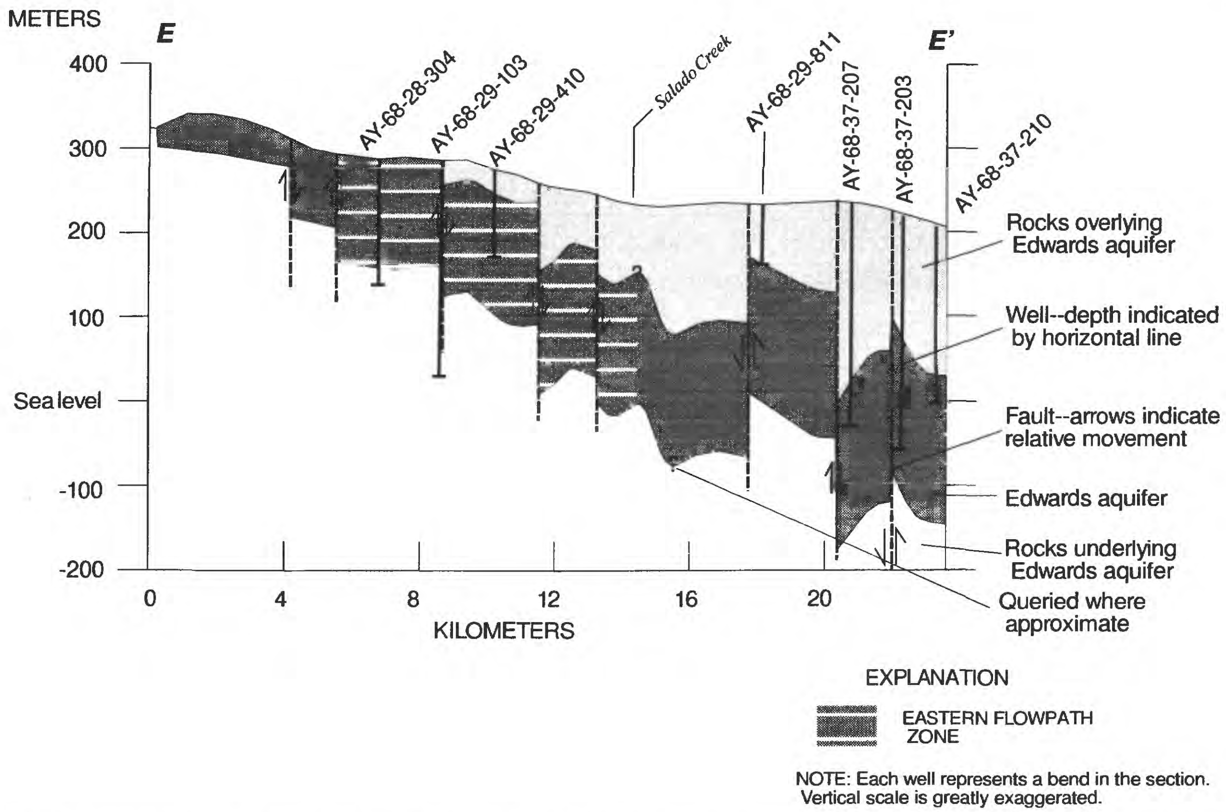


Figure 27a. Hydrogeologic section *E–E'* across the Edwards aquifer eastern flowpath, San Antonio region, Texas.

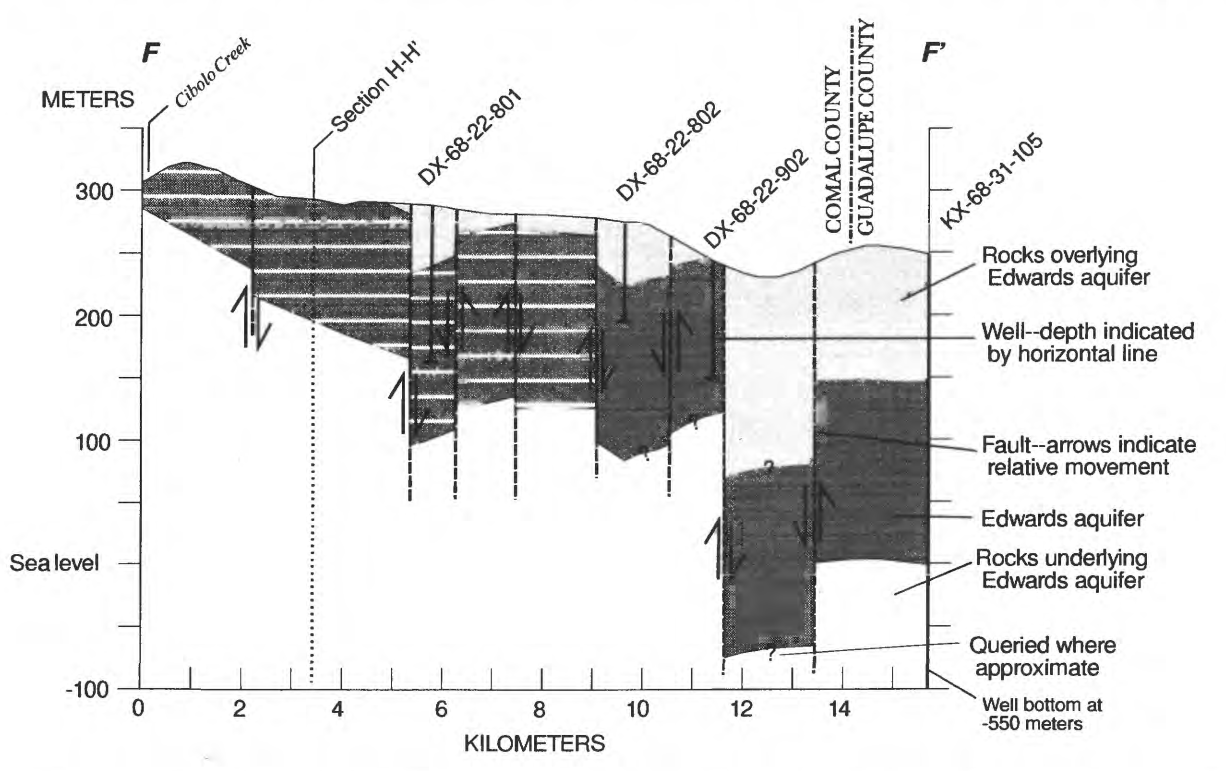


Figure 27b. Hydrogeologic section *F–F'* across the Edwards aquifer eastern flowpath, San Antonio region, Texas.

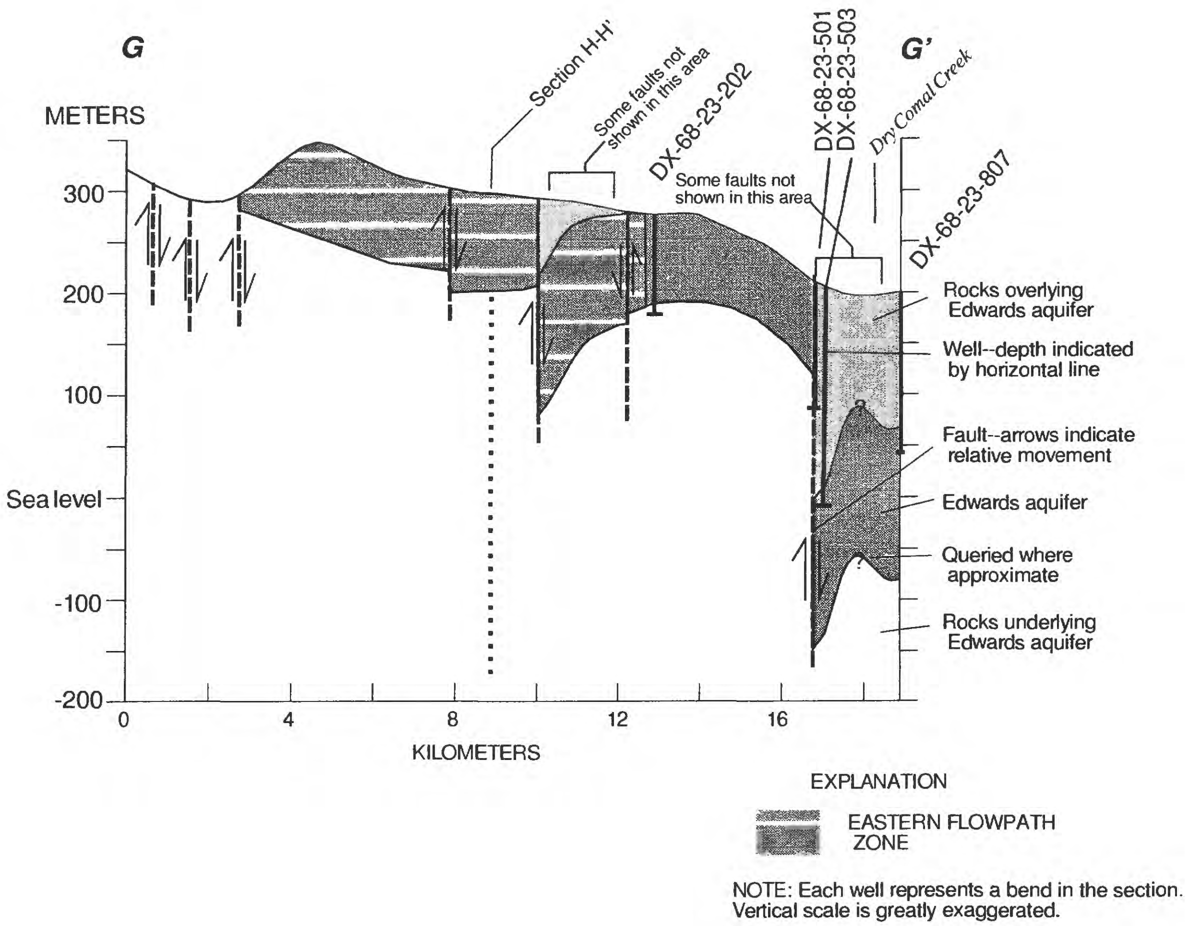


Figure 27c. Hydrogeologic section *G–G'* across the Edwards aquifer eastern flowpath, San Antonio region, Texas.

flow with few or no vertical pathways of movement and fault displacement.

Water-Level Gradient

Water-level measurements made during September 1952 and July–August 1989 are shown in figures 30 and 31. Water-level gradients for the eastern flowpath are not as steep as those for the western Medina flowpath, and water levels in the eastern flowpath are less consistent from well to well. Part of the contrast between the water-level gradients of the western Medina flowpath and those of the eastern flowpath is caused by the nature of local flow lines in the eastern flowpath area. The many public water-supply wells in northern Bexar County cause water levels to be less consistent from recharge to discharge. Withdrawals from these wells in and just south of the recharge area create ephemeral depressions on the potentiometric surface.

Large withdrawals of ground water in the San Antonio area, regardless of the antecedent recharge, tend to move water toward the south from the recharge area in Bexar County. Under pre-development conditions, water flowed from the recharge area in Bexar County toward Comal, Hueco, and San Marcos Springs; under present conditions, such flow probably will occur only during periods of relatively small well withdrawals. Comal Springs fault is a flow barrier between the recharge area on the northwest and the confined zone on the southeast in part of northeastern Bexar and most of Comal County (pl. 3). The quantity of water transferred across this fault barrier, if any, is unknown.

Geochemical Gradient

Selected properties and constituents of water samples from seven wells in the eastern flowpath are listed in table 7. The water-chemistry statistics are similar to those for 1968–75 and 1985–90 (table 5). The

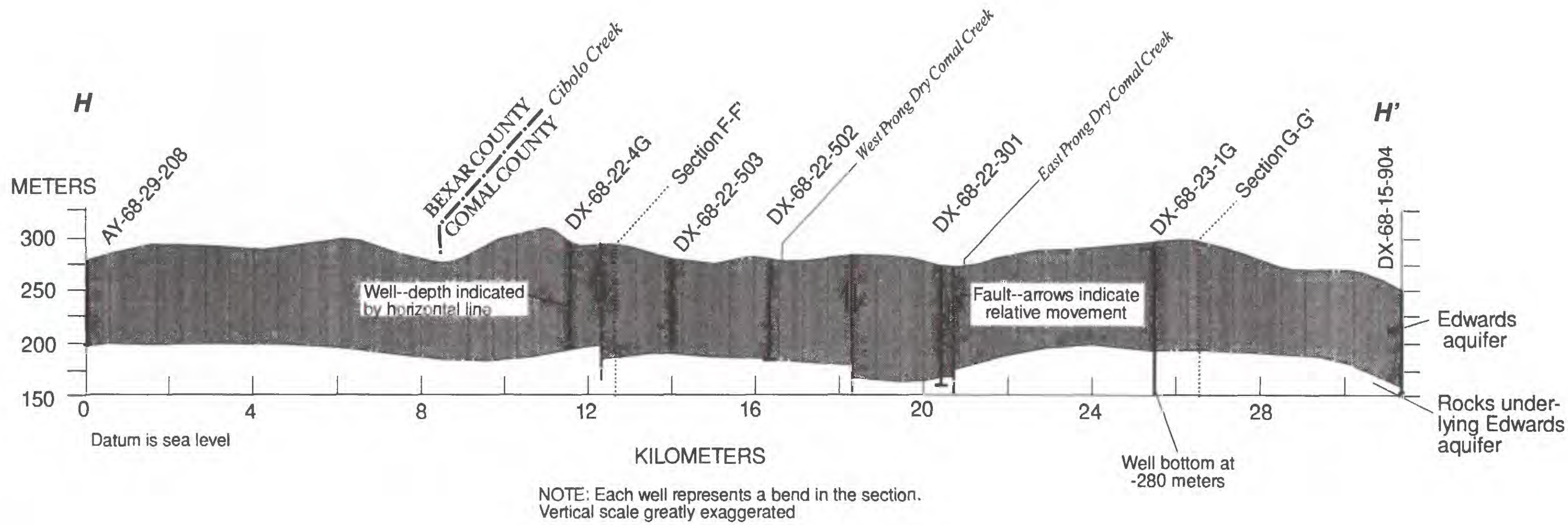


Figure 28. Hydrogeologic section *H–H'* along the Edwards aquifer eastern flowpath, San Antonio region, Texas.

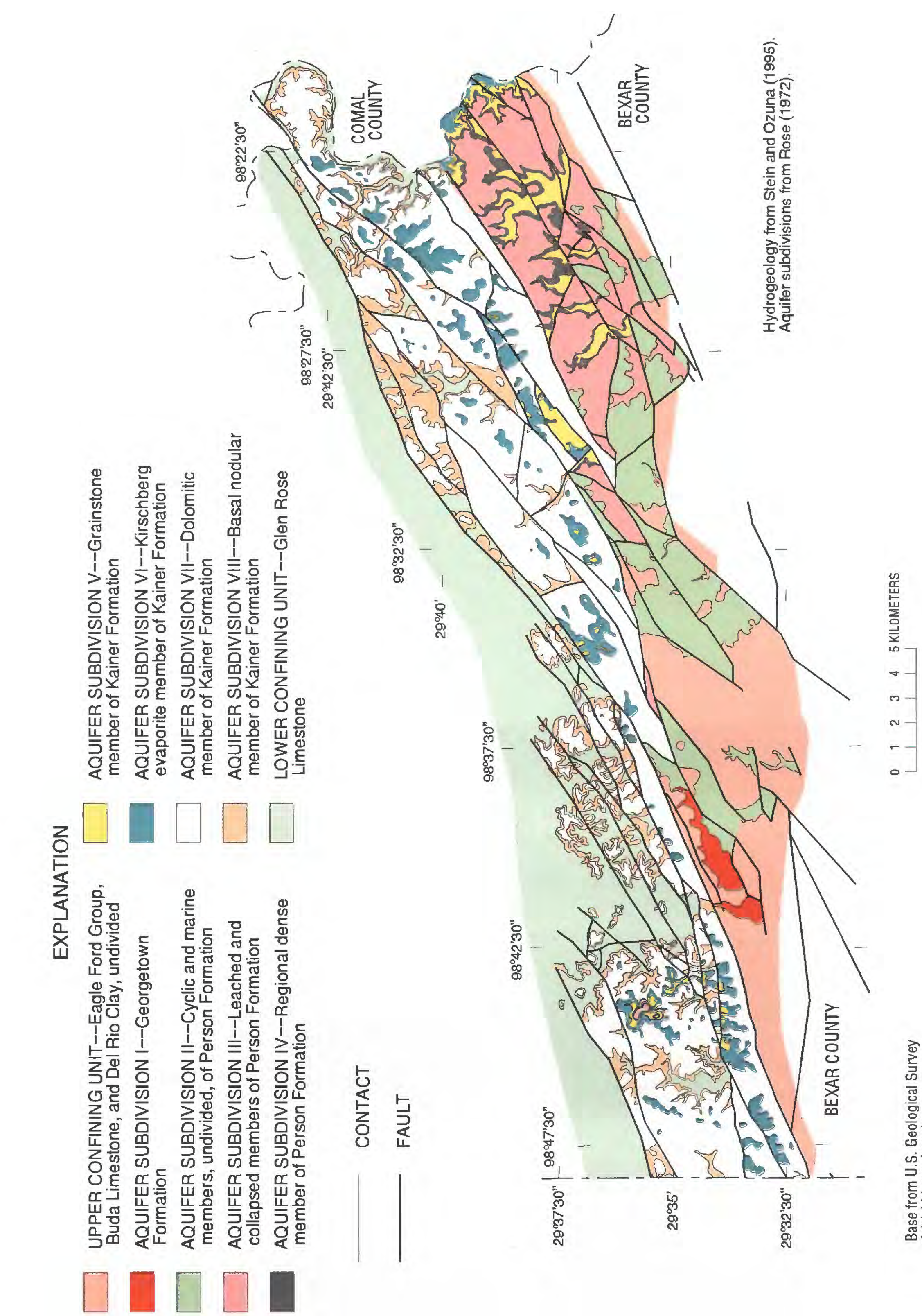


Figure 29. Surface geology of the Edwards aquifer subdivisions, San Antonio region, Texas.

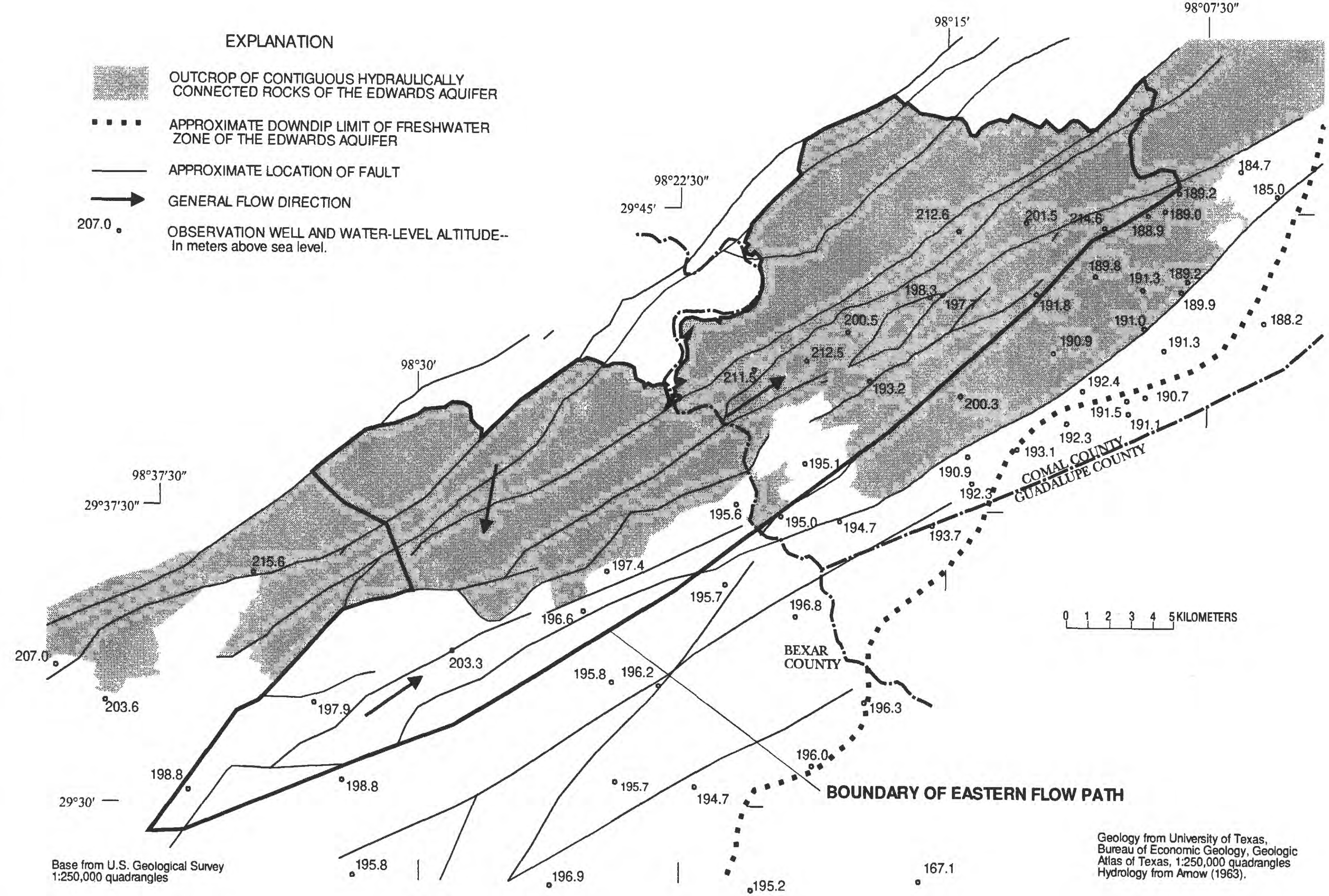


Figure 30. Water levels in observation wells in the Edwards aquifer eastern flowpath area, San Antonio region, Texas, September 1952.

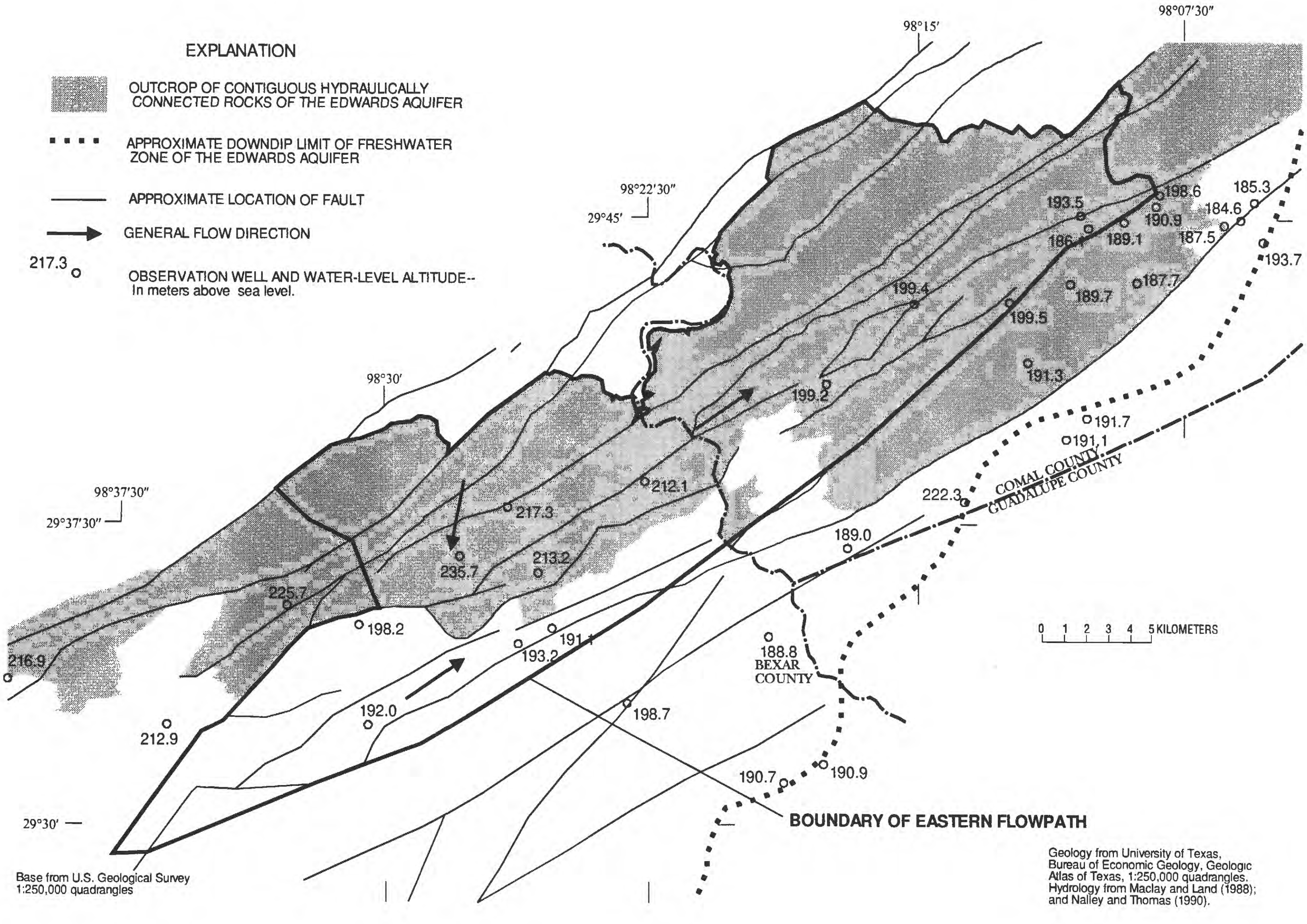


Figure 31. Water levels in observation wells in the Edwards aquifer eastern flowpath area, San Antonio region, Texas, July–August 1989.

concentrations indicate that water in the eastern flowpath is distinctly different in chemical character from other flowpaths in the Edwards aquifer; however, no identifiable natural reason exists for disparity between the chemistry of water recharged in Bexar County and the chemistry of water that flows through the western Medina flowpath.

Dissolved Ions

The locations of wells sampled periodically during 1968–90 for inorganic ions and wells sampled during 1989–90 for volatile organic compounds are shown in figure 32. A series of boxplots indicating summary statistics for specific conductance, dissolved calcium, dissolved magnesium, alkalinity, dissolved sulfate, and dissolved chloride is shown in figure 33.

The mineralogy of the Kainer and Person Formations in the eastern flowpath is similar to the Devils River Limestone in the western Medina flowpath. Both sets of rocks primarily are calcitic limestones with small amounts of dolomite. The calcium bicarbonate water must be diverted towards the northeast by the Northern Bexar faults, other unmapped faults, or the magnitude of ground-water flow from the west-southwest.

Dissolved solids, dissolved calcium, alkalinity, and dissolved chloride concentrations in water samples for 1968–88 are shown in figure 34. Despite the variation in the concentrations, sample concentrations from most wells either increased or decreased during the period. The upward trends in concentrations observed in wells AY–68–28–903, AY–68–29–401, AY–68–29–405, and AY–68–29–503 could be caused in part by: (1) increased development (disturbance of the soil and underlying bedrock) in the recharge area; (2) mineralized effluent from developed areas infiltrating in the recharge area; or (3) increased dissolution of aquifer material for other unknown reasons.

Tritium

The locations of wells in or near the eastern flowpath area that were sampled and analyzed for tritium concentrations during 1975 and 1985 are shown in figure 35. Most tritium concentrations in water samples from the eastern flowpath area are higher than the concentrations in water samples from the western Medina flowpath area. All or most of the water within the eastern flowpath might have been recharged since about 1952. The high tritium concentrations shown in figure 35 are similar to tritium concentrations expected in the recharge area.

A water sample collected from a well about 300 m south of the southern edge of the recharge area, where the Edwards aquifer is only 70 m below land surface, had tritium concentrations of only 0.5 TU (Nov. 4, 1968) and 1.2 TU (May 5, 1969). Although a fault is between the well and the recharge area, the fault has a relative displacement less than about 50 percent of the Edwards aquifer thickness. The fault might hinder flow directly from the recharge area to the well; however, it probably would not cause the blockage of substantial quantities of high tritium water. If water in the recharge area peaked in tritium concentrations around 1963 when precipitation peaked in tritium (T.B. Coplen, U.S. Geological Survey, written commun., 1989), the water in the recharge area should have had a tritium concentration of greater than about 15 TU, similar to tritium concentrations in the wells sampled in Comal County in the eastern flowpath (fig. 35). Because tritium concentrations were so small, one or more of the following is probable: (1) high tritium water had not traveled about 300 m from the recharge area to the well between 1952 and 1969; (2) the mass of water within the recharge area in Bexar County was so great that the recent (post-1952) recharge volumes were insignificant in comparison and did not substantially affect the tritium concentration of the recharge area; or (3) the movement of water from the recharge area into the confined zone is much more complex than hypothesized.

Ground-water samples from wells in the Edwards aquifer south of the eastern flowpath have highly variable tritium concentrations. Such variability indicates that either: (1) ephemeral recharge occurs in the confined zone south of the eastern flowpath, perhaps near San Pedro or San Antonio Springs; or (2) substantial volumes of water are drawn from the eastern flowpath area toward wells south of the eastern flowpath. The second possibility has important implications for the movement of contaminants that might enter the Edwards aquifer through parts of the eastern flowpath area.

Stable Isotopes

Stable-isotopic ratios in water samples from wells in and near the eastern flowpath area indicate that virtually all the water in the eastern flowpath of the Edwards aquifer is from precipitation and has not been subjected

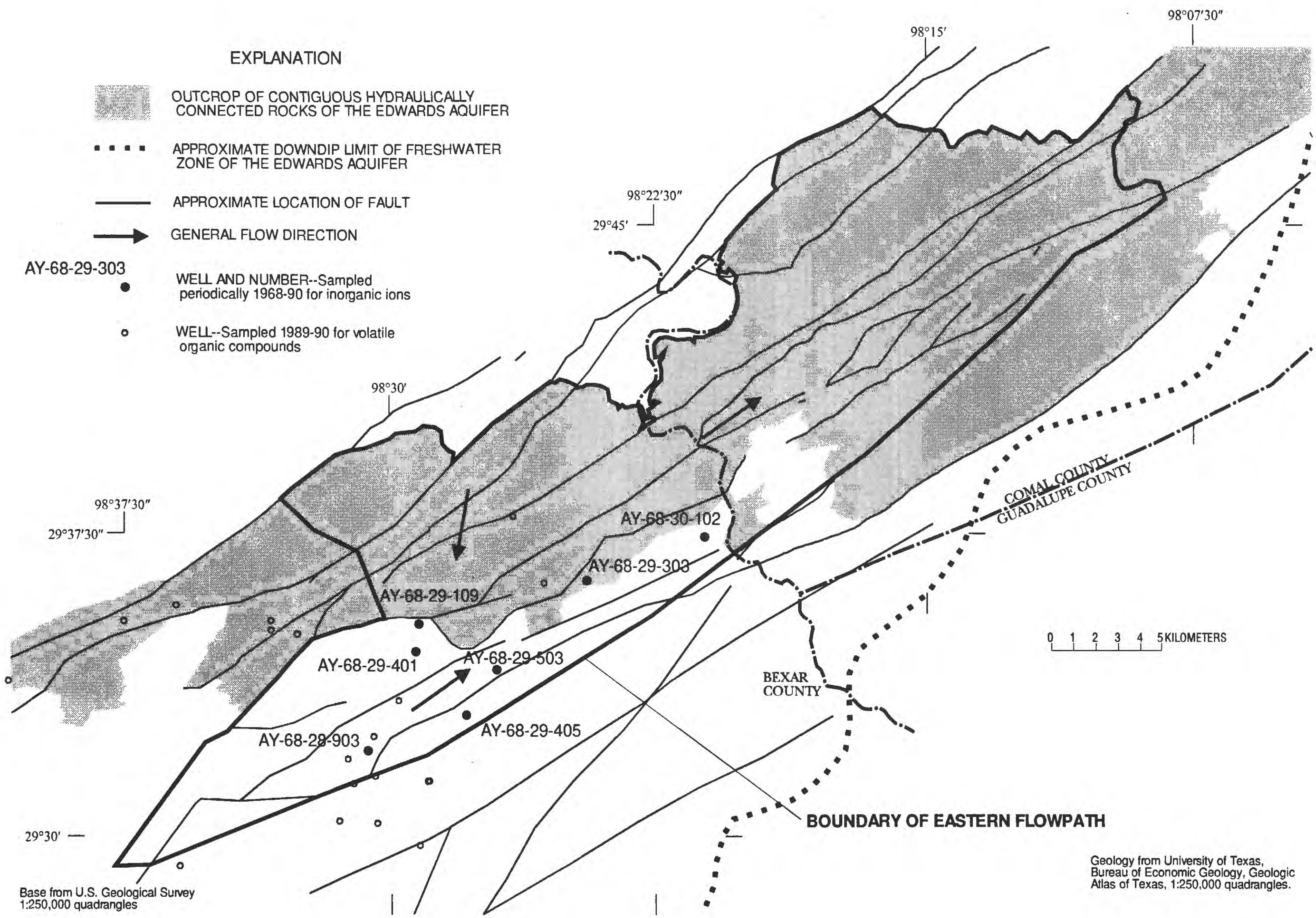


Figure 32. Locations of wells sampled periodically during 1968–90 for inorganic ions and wells sampled during 1989–90 for volatile organic compounds in the Edwards aquifer eastern flowpath area, San Antonio region, Texas.

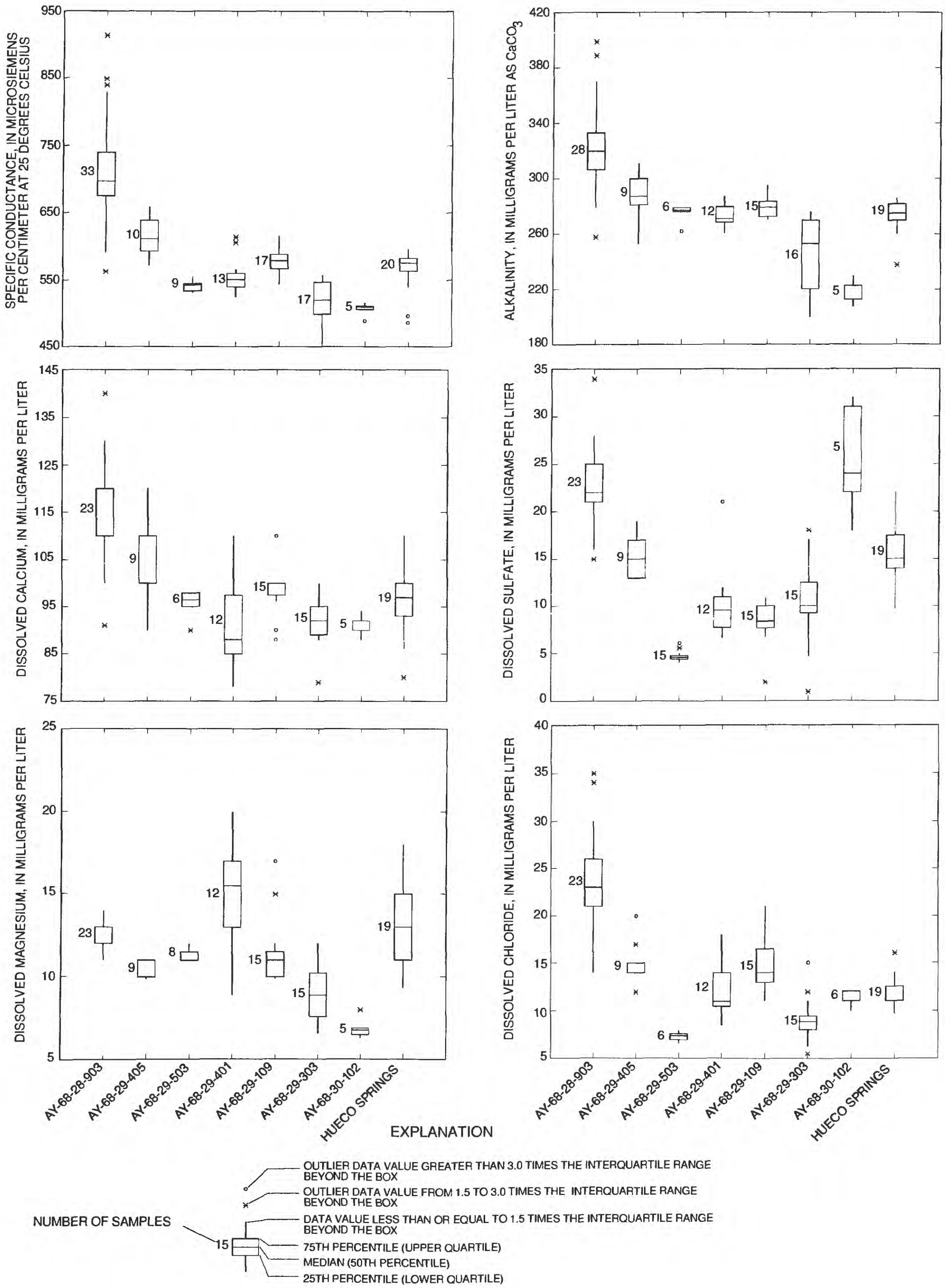


Figure 33. Range and distribution of selected physical properties and constituents in water samples from seven wells in the Edwards aquifer eastern flowpath area and from Hueco Springs, San Antonio region, Texas, 1968–90.

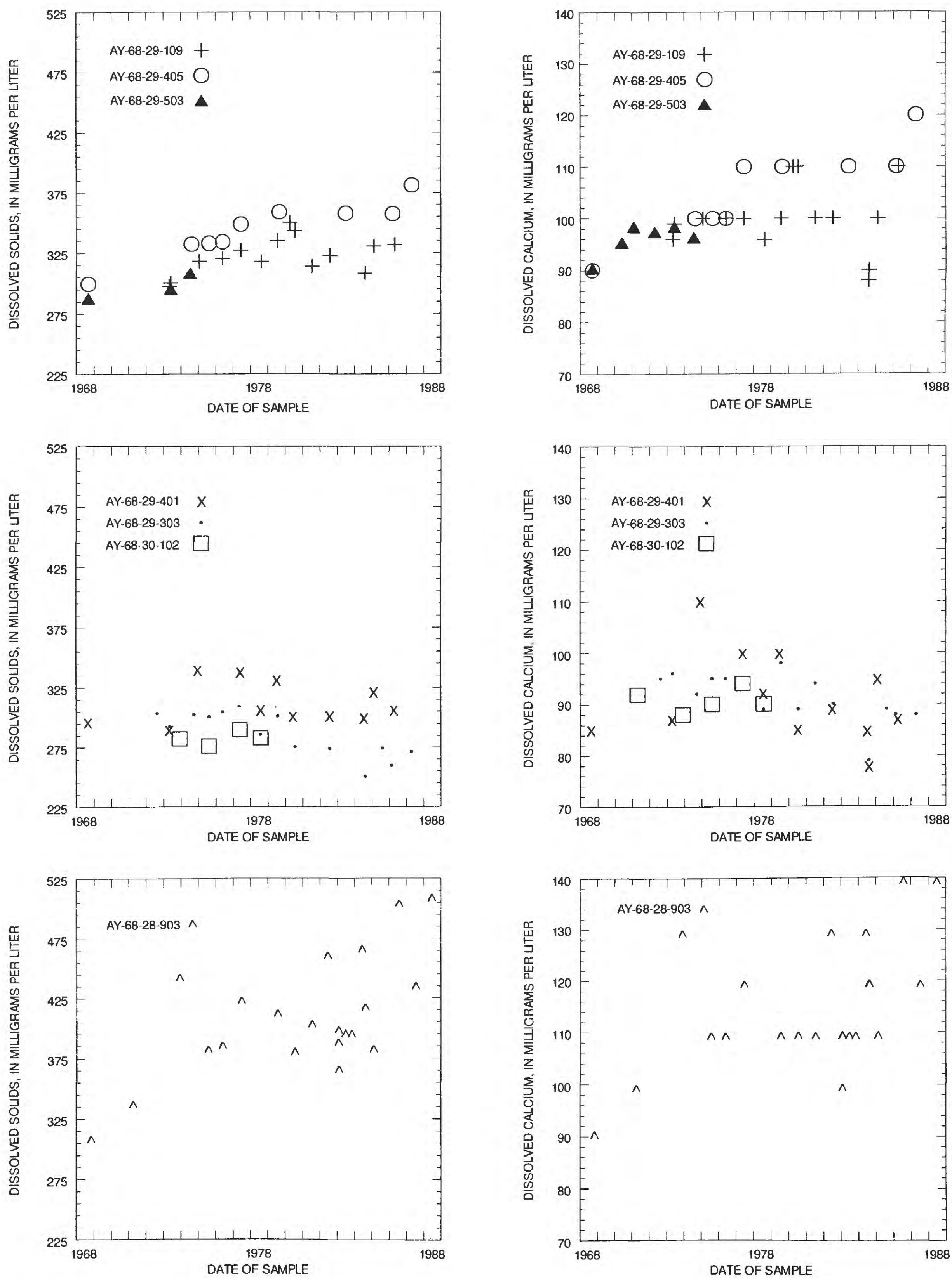
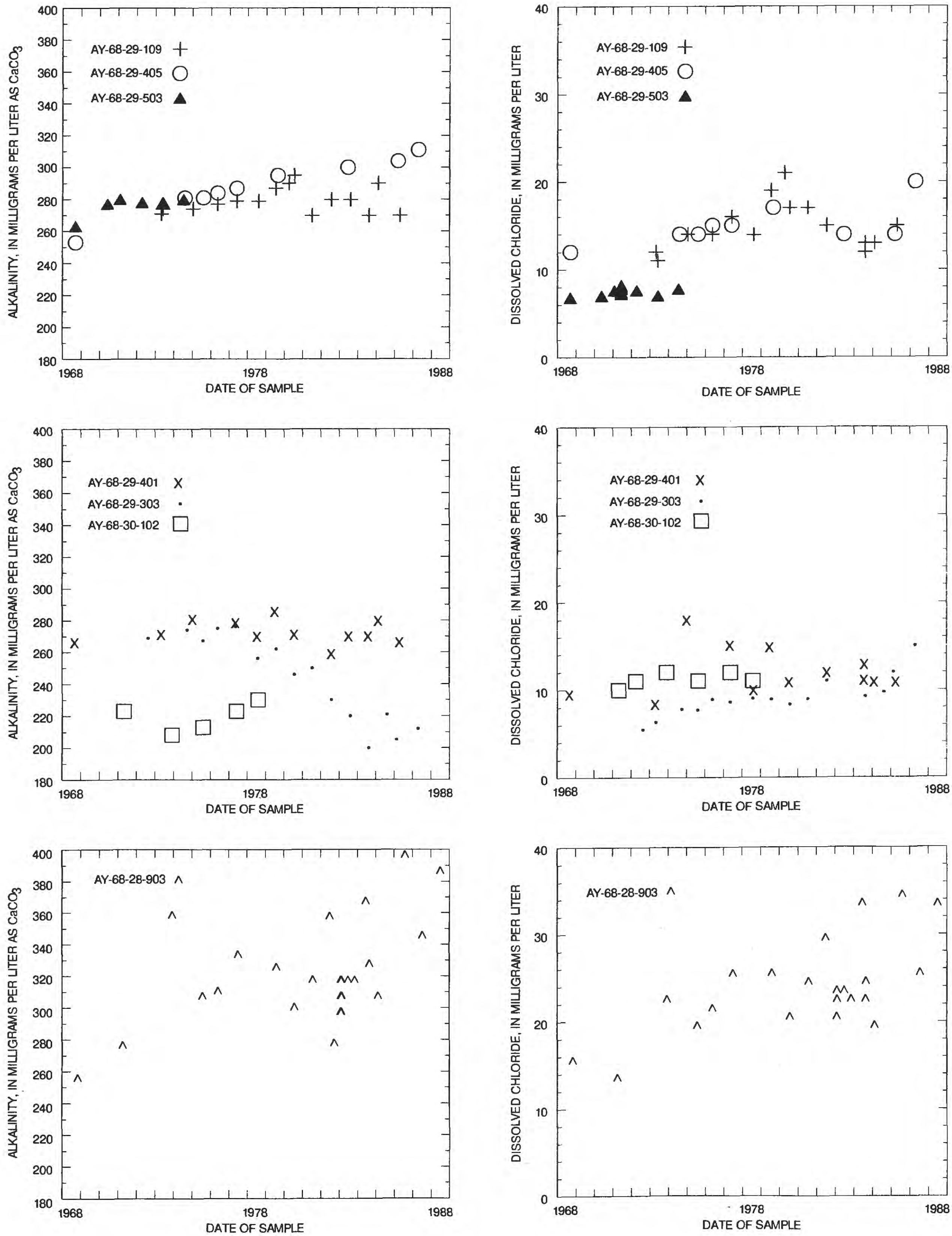


Figure 34. Selected constituents in samples from seven wells in the Edwards aquifer eastern flowpath area, San Antonio region, Texas, 1968–88.


AY-68-29-109
AY-68-29-405
AY-68-29-503
AY-68-29-401
AY-68-29-303
AY-68-30-102
AY-68-28-903
ALKALINITY, IN MILLIGRAMS PER LITER AS $CaCO_3$
DISSOLVED CHLORIDE, IN MILLIGRAMS PER LITER
DATE OF SAMPLE
1968
1978
1988

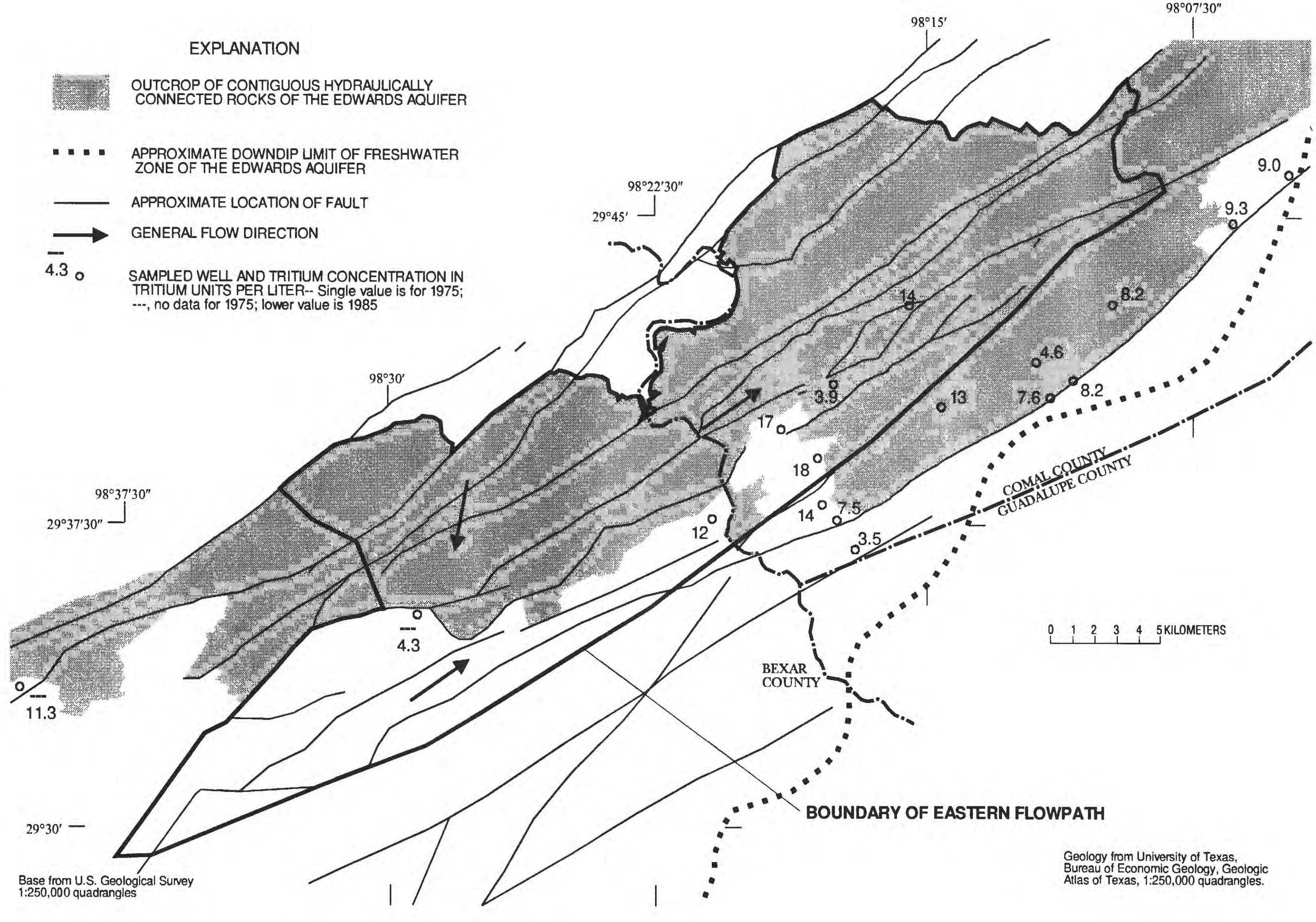


Figure 35. Locations of wells sampled for tritium concentrations in the Edwards aquifer eastern flowpath area, San Antonio region, Texas, 1975 and 1985.

to physical or chemical processes that would affect the ratios.

Volatile Organic Compounds

Locations of wells sampled for trichlorofluoromethane in 1976 by Thompson and Hayes (1979) and in 1977 by Randall and others (1977) are shown in figure 36. Thompson and Hayes (1979) analyzed the data for trichlorofluoromethane concentrations to evaluate the potential for using trichlorofluoromethane as a tracer in ground-water-flow systems. The concentrations from wells in central and northeastern Bexar County and from wells in Comal County were much higher than expected. Thompson and Hayes (1979) speculated that the higher concentrations were from a point source that might have been injected into the Edwards aquifer through a well. The trichlorofluoromethane plume proved to be a useful tracer for flow in the Edwards aquifer from north-central San Antonio to Comal Springs (fig. 1) and several kilometers to the northeast of Comal Springs. A high trichlorofluoromethane concentration (about 20 ppt) was detected in a sample from Comal Springs in 1976 (Thompson and Hayes, 1979, p. 551–552). The high concentration indicates that the amount of trichlorofluoromethane in the Edwards aquifer must have been very high to avoid complete dilution because Comal Springs is the discharge point for most of the water in the Edwards aquifer south and west of Comal Springs that is not withdrawn through wells.

The flow pattern determined by Thompson and Hayes (1979) deviates from the flow patterns determined by Maclay and Land (1988) and from the eastern flowpath. The data available for the area near the Bexar-Comal County line just southeast of the recharge area are insufficient to determine if trichlorofluoromethane contaminated water continued to flow toward Comal Springs on the upthrown side of Comal Springs fault or only on the downthrown side. Maclay and Land (1988) and Maclay and Small (1984) determined that most flow to Comal Springs is from the downthrown side of Comal Springs fault.

The data from Thompson and Hayes (1979) relate to the shape and nature of the zone contaminated by trichlorofluoromethane. The trichlorofluoromethane contaminated wells are along a line roughly from the source in north-central San Antonio to Comal Springs. For the most part, the contaminated wells are not within the boundary of the eastern flowpath area. If eastern flowpath water had been drawn southward toward pumping centers in San Antonio, the plume or line of contaminated wells would not be nearly as linear as it appears, or it might have been dispersed in the area of large withdrawals in northern San Antonio. Therefore, either the water in the eastern flowpath is strongly diverted toward the northeast (toward Comal or Hueco Springs), or the volume of flow diverted southward from the eastern flowpath area is small.

The extremely small trichlorofluoromethane concentrations (fig. 36) detected by Randall and others (1977) in water samples from wells distributed around Bexar and Comal Counties indicate that much of the mass of trichlorofluoromethane from the point source inferred from the Thompson and Hayes (1979) data had passed through or dispersed in the Edwards aquifer. Most likely, the major part of the mass of trichlorofluoromethane had discharged through wells or Comal Springs.

Water samples were collected and analyzed for volatile organic compounds during 1989–90; those that exceeded the detection limit for trichlorofluoromethane and trichloroethylene are shown in figure 37. The samples were analyzed to determine if the mass of trichlorofluoromethane had completely passed through the Edwards aquifer and if there were continuous sources of trichlorofluoromethane or other similar organic compounds that could be traced along flowpaths. The results and method reporting limits for the compounds analyzed are listed in table 10.

Trichlorofluoromethane concentrations, in general, were much smaller during 1989–90 than during 1976–77. The mass of trichlorofluoromethane detected by Thompson and Hayes (1979) has moved out of the Edwards aquifer and probably was the result of a short-term point-source injection, although the actual process of how trichlorofluoromethane entered the Edwards aquifer is undetermined. Results for other volatile organic compounds indicate a continuous source of contamination to the Edwards aquifer (table 10) and, according to Buszka (1987), the most likely source is from an abandoned landfill (fig. 37).

A condition that possibly could result in a zone of uncontaminated water south of the contaminated section of the eastern flowpath is a physical barrier that is not directly related to faults. The quantity of water flowing from the west through this narrow zone is so large that it might prevent flow from the recharge area in Bexar County from moving across the boundary between the eastern flowpath and the rest of

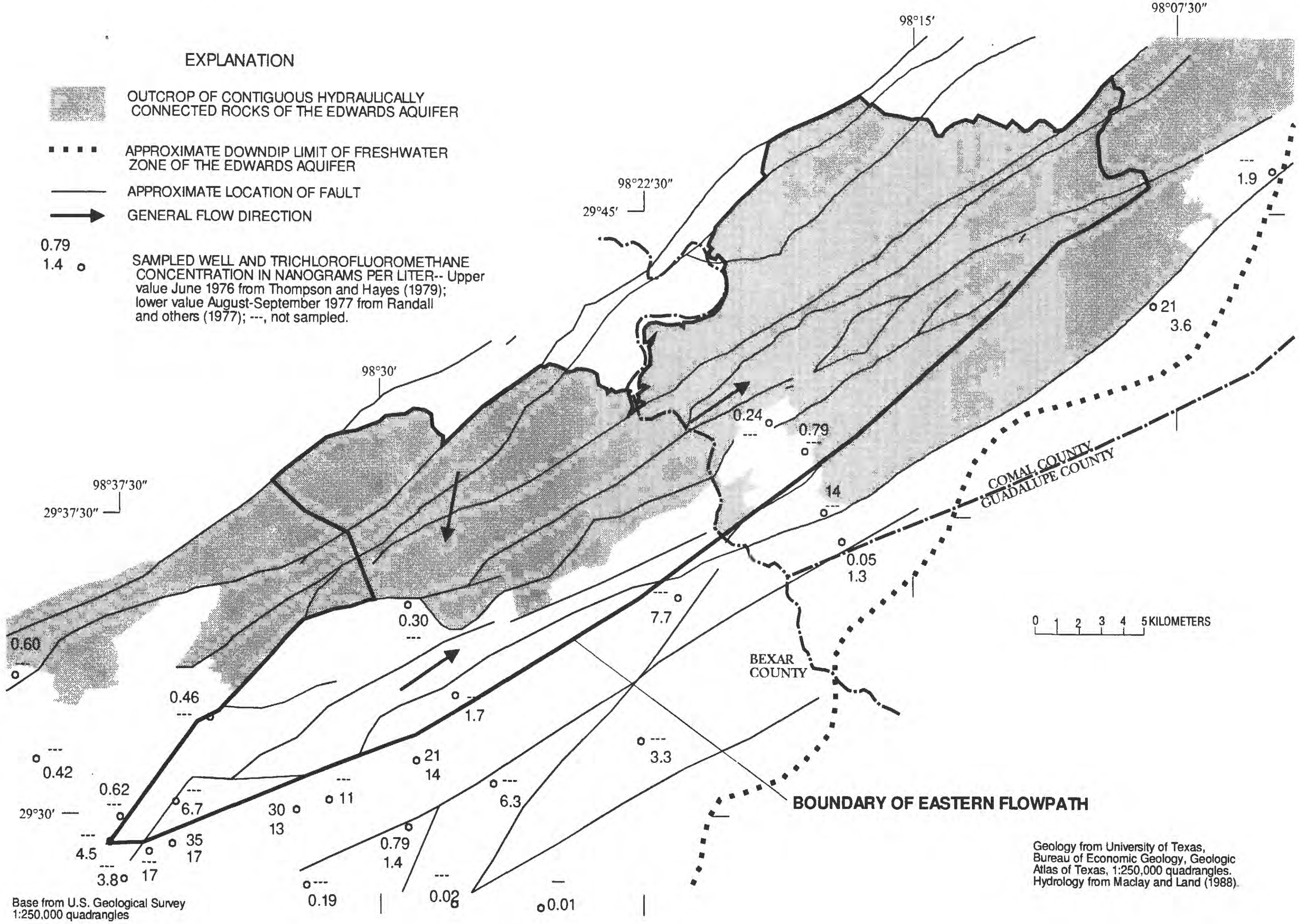


Figure 36. Locations of wells sampled for trichlorofluoromethane concentrations in the Edwards aquifer eastern flowpath area, San Antonio region, Texas, 1976 and 1977.

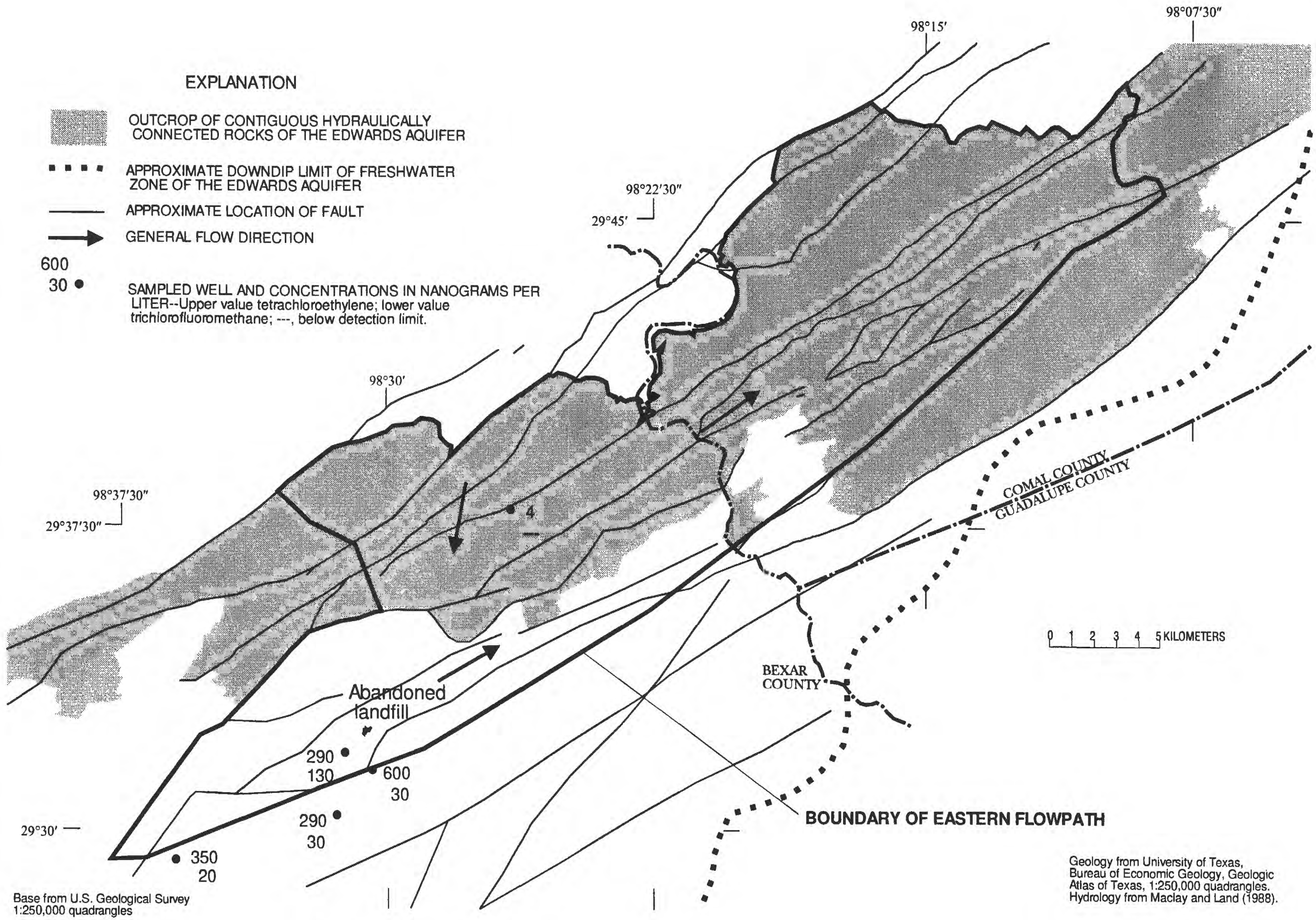


Figure 37. Locations of wells sampled for volatile organic compounds in the Edwards aquifer eastern flowpath area, San Antonio region, Texas, 1989–90.

Table 10. Analyses of selected volatile organic compounds in water from the Edwards aquifer, San Antonio region, Texas, 1989–90

[ng/L, nanograms per liter; <, compound not detected in sample greater than reporting limit value; --, measurement not made; *<, compound detected in sample at concentration less than value, detection may be caused by lab or shipping contaminant]

Sample or well no.	Date sampled	No. of duplicate analyses	Tetra-chloro-ethylene (ng/L)	Trichloro-ethylene (ng/L)	cis-1,2-Dichloro-ethylene (ng/L)	Vinyl chloride (ng/L)	Dichloro-difluoro-methane (ng/L)	Trichloro-fluoro-methane (ng/L)	1,2-Dichloro-benzene (ng/L)	1,4-Dichloro-benzene (ng/L)
R–12	06/06/89	1	<200	<200	<200	<200	200	<200	<200	1,700
				Bexar County						
AY–68–21–804	06/04/90	3	4	<4	<2	--	<4	<3	<1	7
AY–68–27–303	08/29/89	2	30	<20	<200	<50	<200	<50	<20	30
AY–68–27–503	08/30/89	1	150	<20	<200	<50	<200	60	<20	60
AY–68–28–102	06/05/90	3	4	<4	<2	--	<4	4	<1	*<4
AY–68–28–203	08/17/89	1	30	300	<200	<50	<200	<50	<20	40
	11/30/89	2	30	<20	<200	<50	<200	<50	<20	<20
AY–68–28–205	08/16/89	1	140	2,600	<200	<50	<200	<50	<20	70
AY–68–28–501	08/16/89	1	70	<20	<200	<50	<200	<50	<20	50
AY–68–29–210	06/06/90	3	7	*<4	<2	--	<4	<3	<1	*<4
AY–68–29–410	08/16/89	1	50	700	<200	<50	<200	<50	<20	40
AY–68–28–903	08/08/89	1	2,700	1,200	1,300	300	<200	140	80	1,100
AY–68–28–917	12/08/89	2	2,500	600	120	60	1,200	1,500	30	400
AY–68–28–919	08/10/89	1	300	<20	<200	70	<200	50	<20	120
	05/16/90	3	200	<4	<2	--	40	130	<1	<4
AY–68–28–920	06/07/89	1	9,000	1,500	1,400	<200	2,400	<200	<200	300
AY–68–28–904	08/08/89	1	500	20	<200	<50	<200	*<50	<20	70
	05/16/90	3	600	30	20	--	310	30	2	6
AY–68–28–905	08/10/89	1	300	<20	<200	<50	<200	*<50	<20	80
AY–68–28–909	08/22/89	2	230	<20	<200	<50	<200	<50	<20	<20
	06/25/90	3	200	10	<2	--	<8	30	<1	*<4
AY–68–28–913	08/09/89	1	200	<20	<200	<50	<200	*<50	<20	100
AY–68–29–405	08/15/89	1	50	<20	<200	<50	<200	<50	<20	20
AY–68–29–416	08/30/89	2	100	<20	<200	<50	<200	50	<20	90
AY–68–29–702	08/22/89	2	260	40	<200	<50	<200	<50	<20	<20

Table 10. Analyses of selected volatile organic compounds in water from the Edwards aquifer, San Antonio region, Texas, 1989–90—Continued

Sample or well no.	Date sampled	No. of duplicate analyses	Tetra-chloro-ethylene (ng/L)	Trichloro-ethylene (ng/L)	cis-1,2-Dichloro-ethylene (ng/L)	Vinyl chloride (ng/L)	Dichloro-difluoro-methane (ng/L)	Trichloro-fluoro-methane (ng/L)	1,2-Dichloro-benzene (ng/L)	1,4-Dichloro-benzene (ng/L)
				Bexar County—Continued						
AY–68–29–703	08/14/90	3	190	8	3	--	50	20	<1	*<4
AY–68–35–102	05/22/90	2	<2	<4	<2	--	<4	<4	<1	*<6
AY–68–35–913	06/25/90	2	*<2	<4	<2	--	<4	<4	<1	<4
AY–68–36–102	06/25/90	3	200	6	<2	--	<8	20	*<4	*<4
AY–68–36–502	06/25/90	2	*<2	<4	<2	--	<4	<3	<1	<4
AY–68–37–101	08/14/90	3	40	<4	<2	--	<4	3	<1	<4
AY–68–37–404	08/14/90	3	<2	<4	<2	--	<4	<3	<1	<4
				Medina County						
TD–68–29–901	05/29/90	3	<2	*<5	<2	--	<4	<3	<1	*<4
TD–68–26–701	06/19/90	2	<2	<4	<2	--	<4	<3	<1	<4
TD–68–33–202	06/13/90	2	<2	<4	<2	--	<4	<3	<1	*<4
TD–68–33–701	06/04/90	2	<2	<4	<2	--	<4	<3	<1	*<4
TD–68–34–104	05/21/90	3	<2	<4	<2	--	<4	<3	<1	*<4
TD–69–40–403	06/04/90	2	<2	<4	<2	--	<4	<3	<1	*<4
TD–68–41–303	06/19/90	2	<2	<4	<2	--	<4	<3	<1	<4
TD–68–42–506	06/04/90	2	<2	<4	<2	--	<4	<3	<1	*<4
TD–69–46–601	05/29/90	2	<2	<4	<2	--	<4	<3	<1	*<4
TD–69–47–301	05/30/90	3	<2	<4	<2	--	<4	<3	<1	<4
				Uvalde County						
YP–69–36–702	06/11/90	2	<2	<4	<2	--	<4	<3	<1	*<4
YP–69–43–606	06/11/90	2	<5	<4	<2	--	<4	<3	<1	*<4
YP–69–45–405	06/11/90	2	<2	<4	<2	--	<4	<3	<1	*<4
YP–69–53–202	06/11/90	2	<2	<4	<2	--	<4	<3	<1	*<4
				Method reporting limits						
	1989		<20	<20	<200	<50	<200	<50	<20	<20
	1990		<2	<4	<2	--	<4	<3	<1	<4

the Edwards aquifer. The condition is possible because the flow system in the Edwards aquifer between the southern boundary of the eastern flowpath and the Alamo Heights horst area is dominated by uncontaminated water moving from the west. If the physical barrier is effective and water levels should decline substantially, then water from the contaminated section of the eastern flowpath would be less likely to move south into the area where most public water-supply wells are located than if there were no physical barrier.

SUMMARY AND CONCLUSIONS

The Edwards aquifer supplies drinking water for more than 1 million people in south-central Texas. The aquifer primarily consists of limestone with some dolostone. Flow of water recharging the aquifer is assumed to be vertical through fractures and solution-enlarged holes or caves or subhorizontal along bedding planes in the recharge area. Faults form barriers to horizontal flow where relative displacement is about one-half or more of total aquifer thickness. Stratigraphic, structural, hydrologic, and geochemical data were analyzed to improve understanding of the movement of water in two major flowpaths in the Edwards aquifer.

A major hydrogeologic factor that affects the pattern of flow of water in the Edwards aquifer is the spatial and temporal distribution of recharge. The amount of precipitation to the recharge area is an important factor of spatial and temporal distribution. Other factors that affect the flowpath of water in the Edwards aquifer are internal boundaries formed by faults or aquifer geometry and the location and rate of spring discharge.

Estimated recharge is obtained from the recharge and catchment areas. Analysis of the estimated recharge during 1982–89 indicated that during years of substantial precipitation, a large part of the net recharge probably is diffuse infiltration of precipitation over large parts of the recharge area. During years with below-normal precipitation, most recharge is leakage from rivers and streams that drain the catchment subbasins. In 1987, a year with intense rainstorms and above-normal precipitation during the first one-half of the year, 87 and 33 percent of the total annual recharge to the Nueces-West Nueces River and Hondo Creek Basins, respectively, were estimated to have resulted from diffuse infiltration of precipitation.

Once recharge has entered the subsurface of the Edwards aquifer, factors such as bedding planes, dissolution porosity, and fractures and faults can affect the movement of water. Caves at the surface and in the subsurface of the Edwards aquifer contain various sizes of dissolution porosity, but few caves in the outcrop area in Bexar County appear to have developed along faults. Many caves and sinkholes in the outcrop area are short pathways for recharge to the Edwards aquifer. Fault surfaces in the Edwards aquifer typically are impermeable to vertical water movement. Some faults that are not near springs might provide vertical or horizontal flowpaths because of possible breccia zones along the fault surface that are more permeable or susceptible to dissolution than surrounding rocks.

Although one-half or more of the Edwards aquifer discharge is from well withdrawals, springs are major regional controls of flow direction because they have a greater effect on developing flow patterns than wells. Most natural discharge from the aquifer is through a few large springs including San Antonio, San Pedro, Comal, San Marcos, Leona, and Hueco Springs. Other than these major springs, subsurface discharge from the Edwards aquifer is negligible.

Two major flowpaths in the Edwards aquifer were selected for intense study. The western Medina flowpath is in parts of Uvalde, Medina, and Bexar Counties. The eastern flowpath is in Bexar and Comal Counties. The average annual recharge is similar for areas traversed by the flowpaths, about 140 million m^3 (about 17 percent of the average annual recharge during 1982–89).

Spatial and temporal trends in water chemistry were examined for the western Medina flowpath and the eastern flowpath. Major dissolved-ion concentrations in water samples collected from the Edwards aquifer were compared for two periods (1968–75 and 1985–90). Samples also were analyzed for isotopic composition of water and trace concentrations of volatile organic compounds to help refine the flowpath from northern Medina County through central Bexar County.

The water-chemistry data collected from wells in the western Medina flowpath indicate that the rocks are undergoing only small amounts of dissolution. The water that discharges through springs or is withdrawn by wells has changed little from the time of recharge. Concentrations of major ions indicate saturation of calcite and undersaturation of dolomite—the two minerals that constitute most of the Edwards aquifer matrix. Tritium data from wells in the western Medina flowpath indicate no vertical stratification of flow. Tritium concentrations in the recharge area of the western Medina flowpath are smaller than would be expected from previous studies and for the amount of recharge the area presumably has received since 1952.

Physical properties (such as alkalinity) and concentrations of individual ions (especially dissolved calcium and dissolved chloride) in water from wells completed in the eastern flowpath area are higher than those associated with water from wells completed in the western Medina flowpath area. The upward trends in concentrations could be caused in part by: (1) increased development (disturbance of the soil and underlying bedrock) in the recharge area; (2) mineralized effluent from developed areas infiltrating in the recharge area; or (3) increased dissolution of aquifer material for other unknown reasons. Most tritium concentrations in water samples from the eastern flowpath area are higher than the concentrations in water samples from the western Medina flowpath area. These tritium concentrations are higher and closer to what would be expected for recharge derived mainly from precipitation.

Specific conclusions of the study are as follows:

1. Stable-isotopic data indicate that the Edwards aquifer water is meteoric and, except for one area, has not evaporated to a large extent or undergone other isotopic-fractionating processes. Evaporation of water from Medina Lake results in a heavier stable-isotopic ratio in water from the lake than in the water that recharges the Edwards aquifer through diffuse infiltration. Heavier stable-isotopic ratios in water samples from two wells south of Medina Lake indicate that water in the Edwards aquifer at the two wells is water that leaked from Medina Lake. The isotopically enriched recharge water from the lakes do not enter either of the selected flowpaths.

2. Tritium data from 1975 and 1985 indicate that the effective porosity of the Edwards aquifer, especially in the recharge area in Medina County (part of the western Medina flowpath) might be much greater than previously estimated. The tritium data also indicate that tritium concentrations might not be vertically stratified in the Edwards aquifer.

3. The chemistry of most of the water in the eastern flowpath in northern Bexar County is substantially different than that of typical water in the Edwards aquifer. The cause of this difference is unknown, but it might be related to conditions unique to the recharge area in northern Bexar County. The different chemistry of the water in the eastern flowpath indicates that the water mass is limited roughly to the area of the eastern flowpath and makes it possible to delineate the zone of uncontaminated water of the western Medina flowpath as it moves through central Bexar County south of the eastern flowpath.

4. Depending on the effectiveness of the boundary between the eastern flowpath and the western Medina flowpath in Bexar County under varying hydrologic conditions, water in the eastern flowpath could be drawn southward toward the large-capacity public water-supply wells in San Antonio.

5. Historical water-level data and the present (1993) observation well network is inadequate to evaluate intermediate or local (well-to-well) water-level gradients within flowpaths because the Edwards aquifer is rarely at steady state and because wells are too widely spaced apart from each other. Furthermore, the data needed to define regional isotropy or anisotropy of the Edwards aquifer properties are not available.

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