Miscellaneous Map No. 38

Structure Map of the San Antonio Segment of the Edwards Aquifer and Balcones Fault Zone, South-Central Texas: Structural Framework of a Major Limestone Aquifer: Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties

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Introduction

Normal faults of the regional Balcones Fault Zone are the principal structural control on the Edwards limestone aquifer and recharge zone, currently the sole source aquifer of San Antonio, Texas. The San Antonio segment of the aquifer, extending over an area of ~3,000 mi^2 in Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties (fig. 1 and map), is the main water resource for residential, agricultural, and industrial use in Bexar, Medina, and Uvalde Counties. Discharge from the aquifer in Comal and Hays Counties feeds springs that are tourist attractions and that have been shown to be critical habitats of endangered species.

The map of the aquifer depicts the subsurface structure of the base of the Del Rio Formation (approximate top of the confined part of the aquifer), the Edwards Group outcrop belt (aquifer recharge area and unconfined part of the aquifer), faults, large relay ramps, and the approximate interface between fresh and saline water. This report summarizes key elements of the aquifer's structural framework and describes structural attributes that affect aquifer recharge, ground-water flow, areal extent, and depth (Hovorka and others, 1995). Faults and large relay ramps control the structural position of the aquifer strata. Some large faults may act as barriers or partial barriers to ground-water flow. Smaller faults and associated joints form local and regional ground-water conduits. Because relay ramps are areas of greater stratal continuity and numerous smaller displacement faults, they can be preferential pathways of ground-water flow.

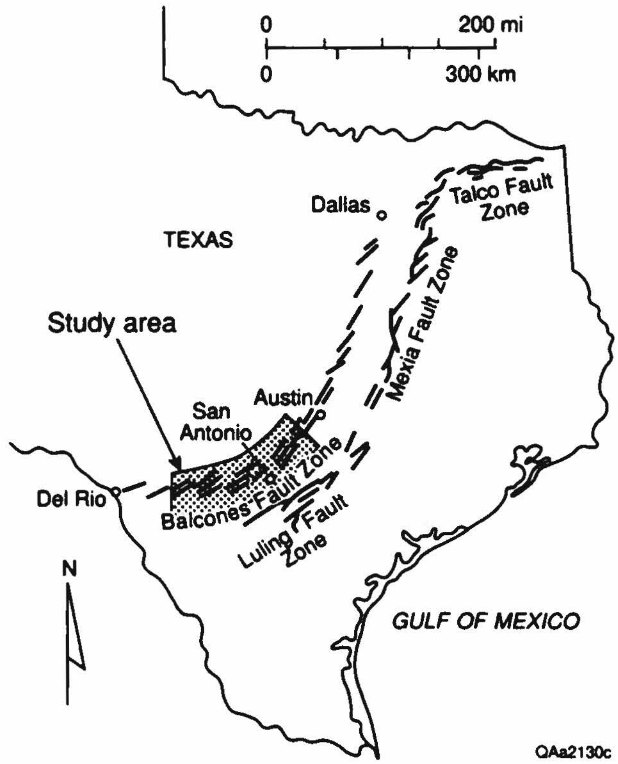

FIGURE 1. Regional setting and location of study area along the Balcones Fault Zone. Faults (solid dark lines) delineating fault zones are schematic.

Previous Work

Our structure of the aquifer (map) builds on many previous studies of the structure and stratigraphy of the Edwards aquifer, particularly the investigation of Edwards Group stratigraphy and facies by Rose (1972), the descriptions of lithologies within the aquifer by Abbott (1973) and Maclay and Small (1986), and the hydrogeologic aquifer cross sections by Small (1986). Previous subsurface structure maps of the Edwards aquifer were published by Klempt and others (1979) and Maclay and Small (1986). We used an updated subsurface data base and recent surface geologic maps to illustrate the structure of the Balcones Fault Zone and Edwards aquifer at a scale that provides more detail than that of previous studies. We are thus able to make new interpretations on fault occurrence, throw, and geometry.

Many surface geologic maps of parts of the Edwards outcrop belt and adjacent areas were reviewed for this study, such as regional 1:250,000-scale maps by Brown and others (1974), Proctor and others (1974), and Waechter and others (1977). More-detailed maps and interpretations that we studied include those by George (1952), Holt (1956), Bills (1957), King (1957), Noyes (1957), Whitney (1957), Arnow (1959), Reeves and Lee (1962), DeCook (1963), Cooper (1964), Abbott

(1966, 1973), Grimshaw (1970, 1976), Newcomb (1971), Shaw (1974), Waddell (1976), Grimshaw and Woodruff (1986), Waterreus (1992), Stein (1993), Small and Hanson (1994), and Stein and Ozuna (1995). Surface geologic maps, constructed at 1:24,000 scale by the senior author, were also used (Baumgardner and Collins, 1991; Collins and others, 1991a, b; Raney and Collins, 1991; Collins, 1992a–d, 1993b–h, 1994a–e, 1995a–j).

Methods

Outcrop geology and subsurface interpretations were compiled on 1:100,000-scale base maps and then reduced to the published 1:250,000 scale (map). The subsurface structure on the top of the Edwards aquifer (base of the Del Rio Formation) was interpreted according to data from about 1,000 wells, in addition to previously reported data on outcropping geologic units and thicknesses of strata overlying the Edwards Group. The major source of data is the stratigraphic interpretation of well logs collected from files of the Edwards Underground Water District (EUWD [now the Edwards Aquifer Authority]) and the surface casing division of the Texas Water Development Board (TWDB). In addition, published well log and stratigraphic data (Rose, 1972; Small, 1986; Schultz, 1992, 1993, 1994) and unpublished well data (TWDB/EUWD files) were compiled. Major structural discontinuities were identified by means of 100-ft contour intervals. The approximate interface between fresh and saline water is from Brown and others (1992) and Schultz (1993, 1994).

The Edwards outcrop section of the map was compiled from various sources. Outcrop geology shown on the east half of the map (east of Lake Medina) was compiled mostly from 1:24,000-scale maps by the senior author (Baumgardner and Collins, 1991; Collins and others, 1991a, b; Raney and Collins, 1991; Collins, 1992a–d, 1993b–h, 1994a–e, 1995a–k). In addition, the surface geology of southern Hays County was modified from 1:250,000-scale mapping (Proctor and others, 1974) and 1:24,000-scale mapping (Grimshaw, 1976; Grimshaw and Woodruff, 1986). Outcrop geology of the Edwards Group on the west half of the map (west of Lake Medina) was compiled from 1:250,000-scale maps by Brown and others (1974), Waechter and others (1977), and Gustavson and Wermund (1985). The apparently greater abundance of faults in the east part of the outcrop belt reflects the greater detail of source maps compiled of that area. The areal boundaries of igneous plugs, based on their mapped geometry in outcrop, might not represent their geometry in the subsurface. The location of subsurface Cretaceous igneous rocks is based on work by Ewing (1990). Cross sections presented herein generalize the faults to near-vertical structures because of the small scale and vertical exaggeration of the sections.

Geologic Setting

Edwards Group strata compose three major depositional belts that trend northwestward across the San Antonio segment of the aquifer: Maverick Basin, Devils River trend, and the San Marcos Platform (figs. 2 and 3). Person and Kainer Formations (Rose, 1972) are found on the San Marcos Platform, and the Devils River Formation (Rose, 1972) was deposited on the platform margin. The West Nueces, McKnight, and Salmon Peak Formations were deposited in Maverick Basin (Smith, 1964). Each formation is made up of a characteristic suite of interbedded lithologies having distinctive hydrologic and petrophysical properties. The Kainer and Person Formations are characterized by high-frequency depositional cycles that include subtidal wackestones and packstones, grain-dominated packstones, grainstones, subtidal gypsum (replaced by calcite), and dolomitic tidal-flat wackestones and grainstones (Hovorka and others, 1996). The Devils River Formation was identified by Rose (1972) where the thick wackestone that defines the base of the Person Formation becomes difficult to identify in outcrop. Core and log examinations show that the Devils River Formation is lithologically similar to the cyclic Kainer and Person Formations across much of its mapped extent, becoming more lithologically homogeneous near the edge of

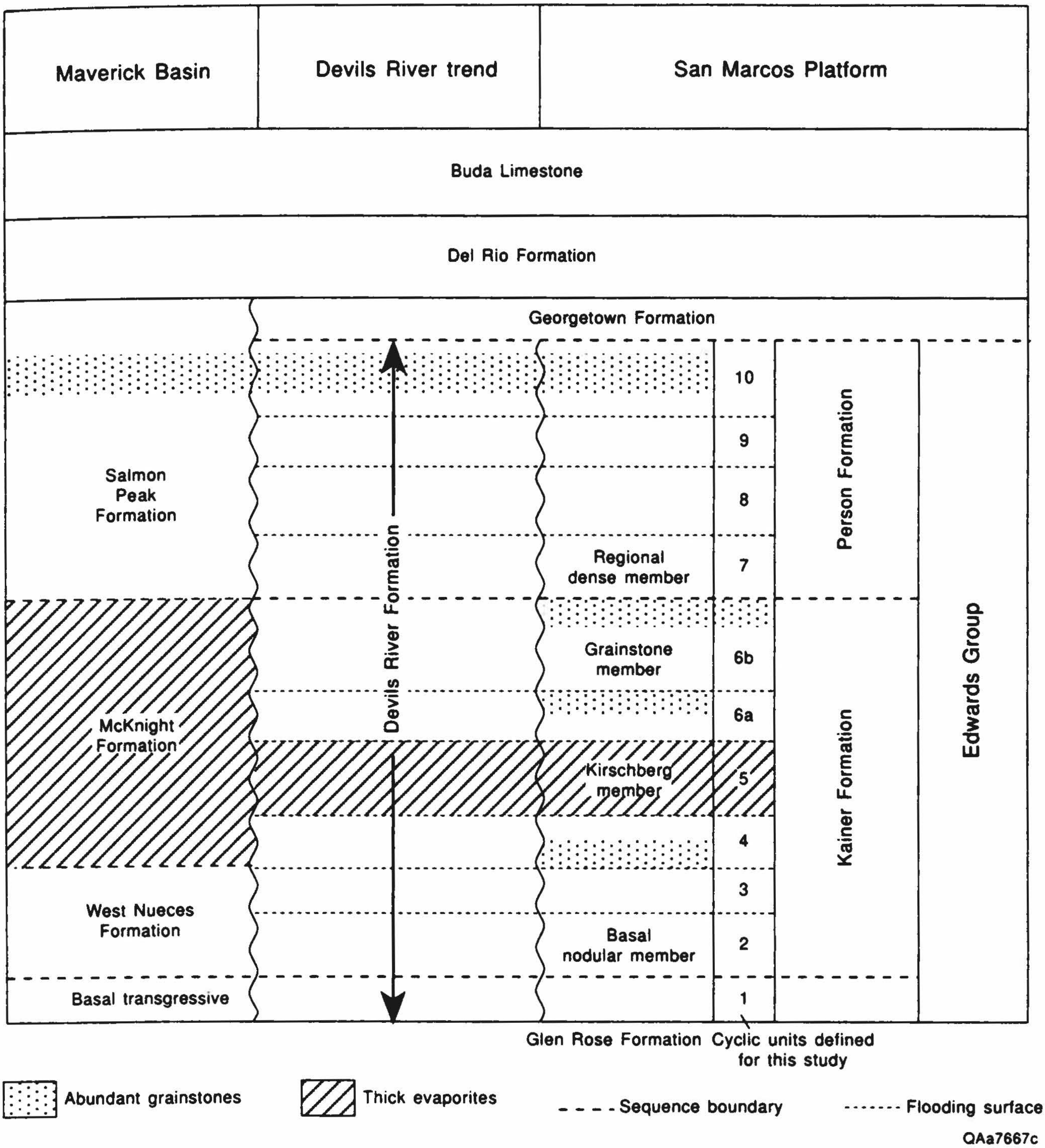

FIGURE 2. Stratigraphy of the Edwards Group. Formation names assigned to the Maverick Basin, the Devils River trend, and the San Marcos Platform from Rose (1972). Cyclic units from Hovorka and others (1994).

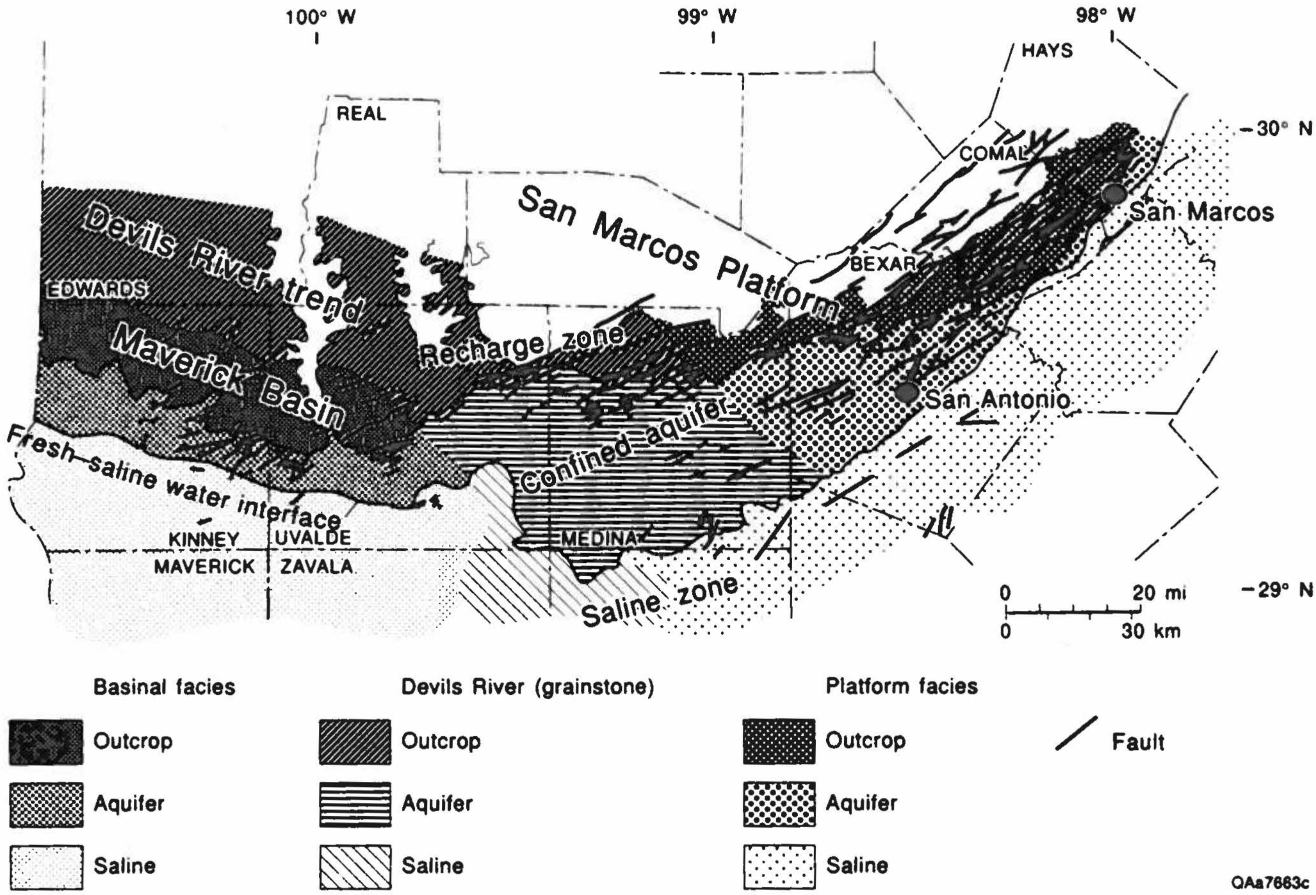

FIGURE 3. Structural, hydrologic, and facies setting of the Edwards aquifer (from Hovorka and others, 1995). The interface between fresh and saline waters (Schultz, 1994) defines the downdip extent of the freshwater aquifer. Three major depositional facies belts that trend oblique to the aquifer are (1) Maverick Basin, (2) Devils River trend, and (3) San Marcos Platform. Fault locations derived from Brown and others (1974), Proctor and others (1974), and Waechter and others (1977).

Maverick Basin (Hovorka and others, 1996). The Maverick Basin facies were deposited in subtidal, slightly deeper water environments (Hovorka and others, 1996). The West Nueces Formation is composed of low-porosity subtidal wackestones and packstones and some grainstones near the top. The overlying McKnight Formation was originally composed of highly cyclic subtidal dark, organic-rich, argillaceous limestones and subtidal gypsum. Gypsum has dissolved from the aquifer and is preserved only in the saline part of the Edwards Group. The Salmon Peak Formation is composed of a thick interval of massive, burrowed, miliolid packstone that coarsens upward.

Edwards strata within the San Marcos Platform facies thicken from ~500 ft at the outcrop belt to ~650 ft downdip in southern Bexar County (Hovorka and others, 1996). In Medina and eastern Uvalde Counties, the Devils River Formation thickens from ~500 ft at the outcrop belt to ~800 ft in southwestern Medina County. The Maverick Basin facies in western Uvalde and eastern Kinney Counties, 600 to 700 ft thick within the outcrop belt, thickens to >1,000 ft in south-central Kinney County. The Edwards Group outcrop belt approximately defines the main recharge area and unconfined part of the aquifer. The subsurface Edwards Group represents most of the confined aquifer. Georgetown limestones overlying Edwards limestones on the San Marcos Platform compose ≤60 ft of low-porosity strata that are commonly grouped with the aquifer. Del Rio clay overlies the aquifer strata (fig. 2). Beneath the Edwards aquifer lie limestone and marl of the Glen Rose Formation. The upper part of the Glen Rose Formation has permeabilities generally lower than those of Edwards strata, and the upper strata of the Glen Rose are thought to define the base of the Edwards aquifer in this area (Maclay and Small, 1986).

The aquifer and recharge zone lie within the Balcones Fault Zone, a regional zone of normal faults along the perimeter of the Gulf Coast Basin (fig. 1 and map). The fault zone, one of the main structural features of Central Texas, extends from near Del Rio east-northeastward to San Antonio, where the zone bends northward through New Braunfels, Austin, Georgetown, and Waco and continues toward Dallas (Murray, 1961; Ewing, 1991). Normal faults composing the zone are either more common or more pronounced between Uvalde and Georgetown, an area that coincides with the Balcones escarpment, a prominent fault-line scarp that is an area of large offset across the fault zone. The fault zone closely follows the trend of the buried Paleozoic Ouachita fold and thrust belt (Flawn and others, 1961). Balcones faults marking the edge of the Texas Coastal Plain are a manifestation of gulfward extension, flexure, and tilting along the perimeter of the Gulf of Mexico. Most displacement on the Balcones Fault Zone occurred during the late Oligocene or early Miocene (Weeks, 1945).

The Edwards aquifer is prolific because it combines high-matrix porosity, which allows the aquifer to store tremendous volumes of water (>200,000,000 acre-ft) of water (Hovorka and others, 1996), with well-developed fracture and karstic conduit systems (Veni, 1987) that allow rapid movement of water. The high porosity reflects the depositional and diagenetic evolution of the limestone and dolomite facies that constitute the aquifer (Hovorka and others, 1996). The diagenetic evolution of porosity in the aquifer has been strongly influenced by Miocene uplift of the Edwards strata along the Balcones fault system and development of the freshwater aquifer (Ellis, 1986; Deike, 1990). The permeability structure of the aquifer is even more closely related to Balcones faulting because conduits and solution features such as caves reflect interaction among fractures, variable solubility of the cyclic strata, and the evolving hydrologic system (Hovorka and others, 1995). High hydraulic conductivity can be related to the proximity of wells to lineaments (Alexander, 1990) and to fractured and faulted intervals in wells (Hovorka and others, 1995). Apertures of many fractures have been enlarged by solution. Although caves and fractures make up only a small percentage of total aquifer porosity, they have hydraulic conductivities about two orders of magnitude higher than those of unfractured, porous Edwards limestones (Hovorka and others, 1995).

Structural Framework of the Aquifer

The structural position of Edwards aquifer strata is controlled by normal faults and associated gentle folds (Collins, 1995k). Faults cut Edwards strata throughout the aquifer, and some of the larger faults partly bound the unconfined aquifer and recharge area (figs. 4 and 5; map). In eastern Kinney County, Edwards strata crop out across the Edwards Plateau (north of the Balcones Fault Zone) and the fault-zone area where the strata gently dip a few degrees into the subsurface. In eastern Kinney and western Uvalde Counties, the subcrop aquifer strata form a relatively narrow band ~2.5 to ~5 mi wide (figs. 4 and 5a; map). Larger displacement faults do not appear to be as common within the aquifer in eastern Kinney County as they are toward the east (figs. 4 and 5), although subsurface data are sparser in Kinney County than in the eastern aquifer areas. In Medina, Bexar, Comal, and western Hays Counties, the generally <10-mi-wide Edwards outcrop

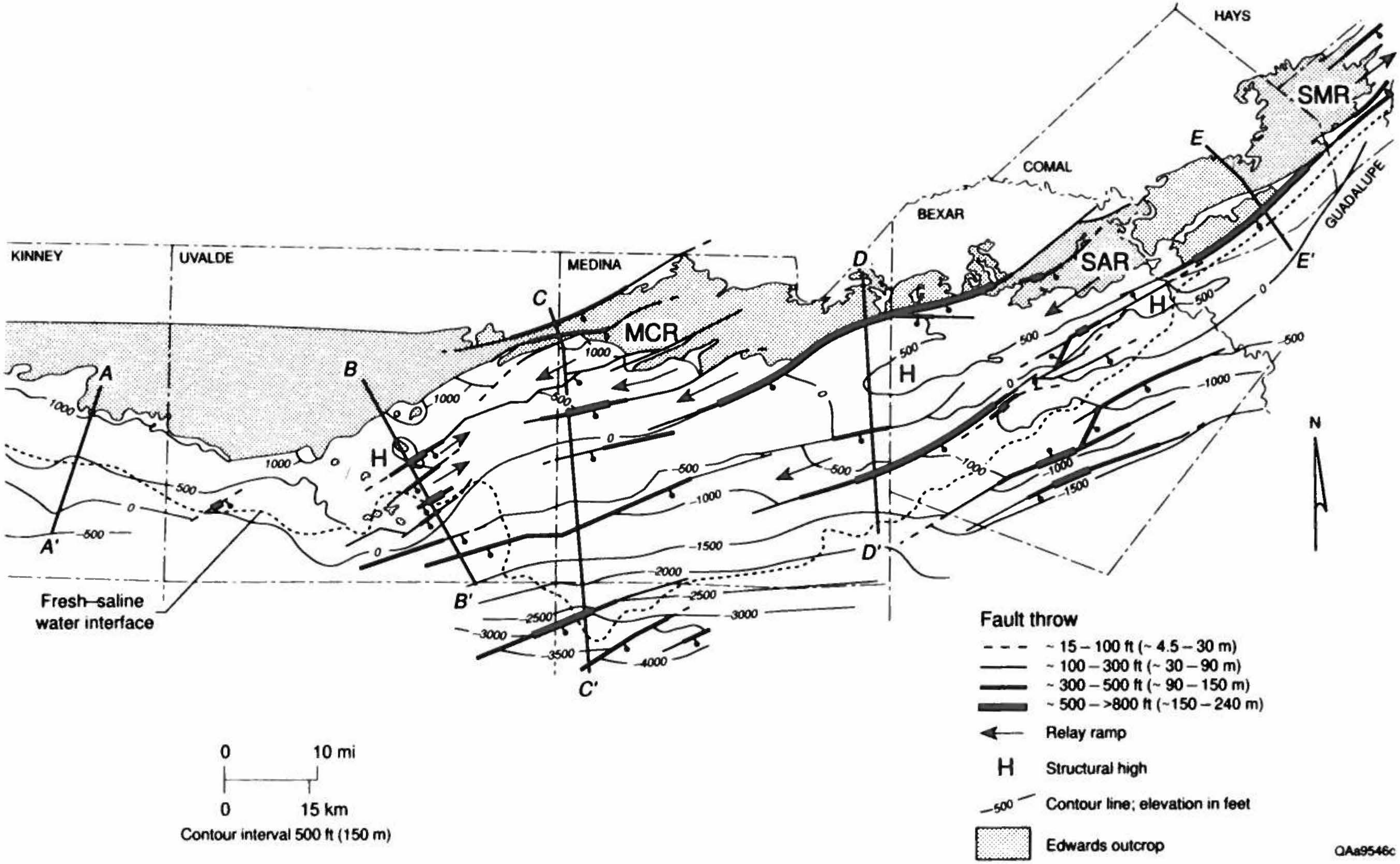

FIGURE 4. Simplified structure of Edwards aquifer strata showing throw of faults. Structural cross sections A–A′ through E–E′ shown in figure 5. MCR = Medina County relay ramp; SAR = San Antonio relay ramp; SMR = San Marcos relay ramp.

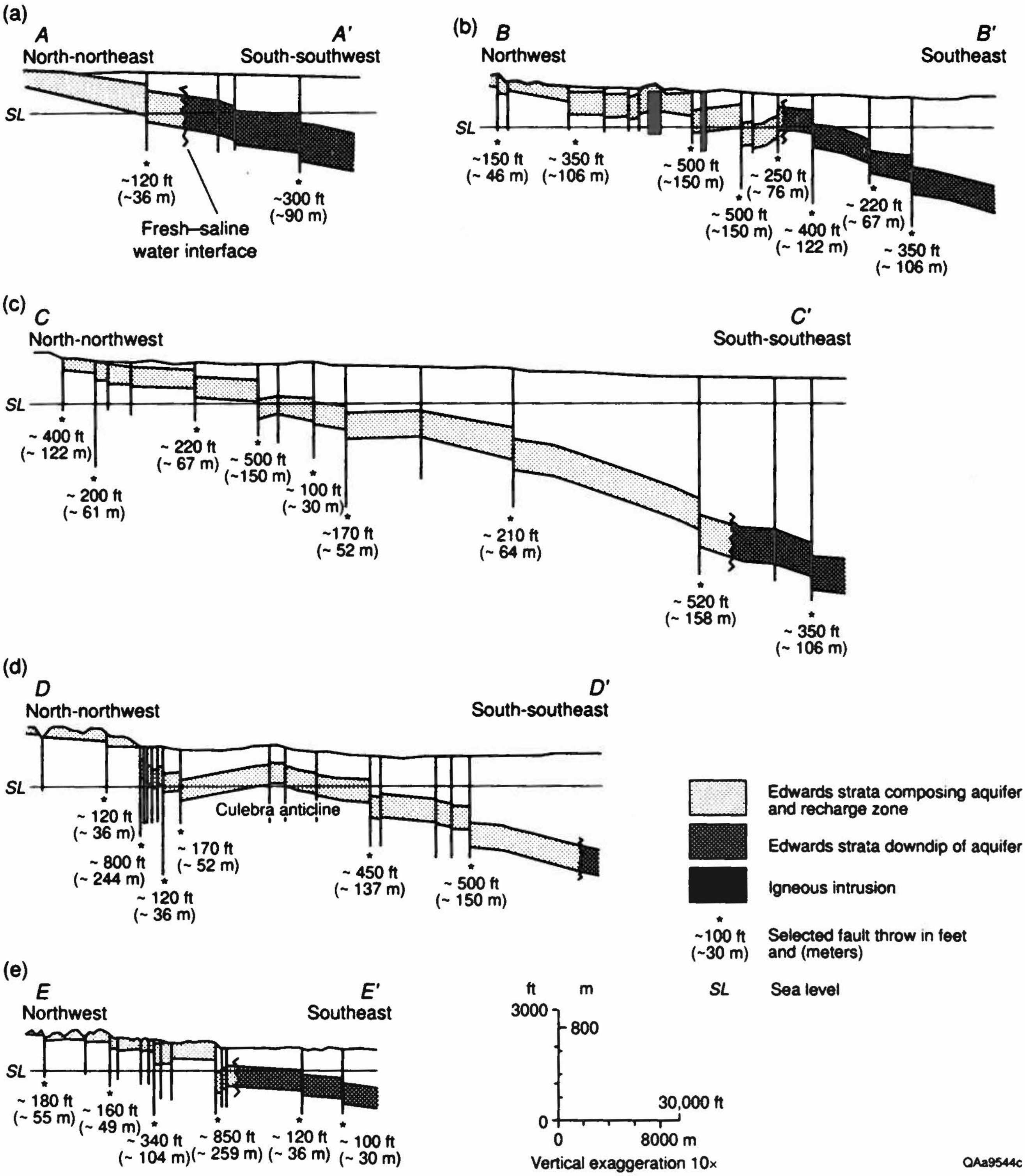

FIGURE 5. North-south structural cross sections A–A′ through E–E′ (a through e, respectively) of Edwards strata composing Edwards aquifer and recharge zone and of Edwards strata downdip of the fresh–saline water interface. Asterisks indicate faults that have >100 ft of throw. Fault throw approximate. Fault dips are simplified as near-vertical structures because of scale and vertical exaggeration of the sections. Lines of section shown in figure 4.

belt (unconfined aquifer and recharge area) is locally absent because of erosion and faulting of the strata (fig. 1 and map). From central Uvalde County and across Medina County, the confined aquifer's width ranges from ~9 to ~30 mi, and structural relief of the aquifer strata is as much as ~1,850 ft (figs. 4 and 5b, c). In Bexar County the confined aquifer's width is between ~4 and ~20 mi, narrowing toward the northeast, and faults have caused >1,400 ft of structural relief (figs. 4 and 5d). In Comal County the confined aquifer is narrow, mostly <1 mi, and the interface between fresh and saline water parallels a large fault bounding the outcrop belt on the southeast (figs. 4 and 5e). Structural relief of the Edwards strata measures ~1,000 ft across the outcrop belt to the fresh–saline water interface in the Edwards subcrop in Comal County.

Several large, structurally high areas exist within the confined aquifer and adjacent to the Edwards outcrop belt (Collins, 1995k). A structural high in central Uvalde County having small outcrops of Edwards strata at its crest trends north-northwestward and plunges southward. Because its trend is oblique to the large crosscutting Balcones faults, the Uvalde structural high may predate Balcones faulting. Small igneous intrusions within this region also cause local structural complexities such as domed or folded strata and faults.

A west-southwest-trending structural high at the Medina–Bexar county line is called the Culebra anticline locally (figs. 4 and 5d). It lies at the downdip end of a large relay ramp in north-central Bexar County. Another west-southwest-trending structural high exists in east-central Bexar County (fig. 4). These two structural highs appear to be fault related, although they are not simple horsts. These areally large structural highs and other smaller structural highs may be related to displacement on large listric faults (M. P. A. Jackson, Bureau of Economic Geology, personal communication, 1995). The presence of dip reversal of strata in the hanging walls of large normal faults (fig. 5) suggests that the faults could be listric at depth and that rollover anticlines exist. It was out of the scope of our study and data base to evaluate the nature of the Balcones faults in the sub-Edwards subsurface to determine whether these faults have listric geometries and sole out into shale with depth or whether they displace the sub-Mesozoic unconformity and the underlying Ouachita rocks, as reported by Ewing (1991).

Most faults within the aquifer study region strike N40° to 70°E and dip southeastward, although some faults dip northwestward. Some subsidiary faults strike northwestward, northward, and eastward. The largest faults have throws in excess of 800 ft, although smaller displacement faults are more common (figs. 4 and 5). Rare outcrops containing larger faults reveal curved fault surfaces having dips between 60° and 85° and displaying striations parallel to nearly parallel to the fault dip. Smaller, subsidiary faults commonly dip between 45° and 85°. Although most smaller faults have striations that parallel or nearly parallel the fault dip, some smaller faults display striations that are oblique to the fault dip (rakes as low as ~65°). The local small faults displaying slightly oblique slip possibly result from local block rotations or local stress-field variations during faulting.

Normal faults of the Balcones Fault Zone are commonly surrounded by zones of highly fractured strata (Collins, 1987, 1993a, 1995k; Reaser and Collins, 1988; Collins and Laubach, 1990; Collins and others, 1992). Abundant fractures (mostly small faults and some joints) adjacent to faults are well connected both laterally and vertically by numerous intersecting and crosscutting fractures. Locally anastomosing fault arrays grade into breccia.

Field mapping of the Edwards outcrop belt within Comal, Bexar, and eastern Medina Counties indicates that the fault zone consists of 2- to 7-mi-wide fault blocks bounded by several long series of southeast-dipping, closely spaced, en echelon large normal faults that have throws ranging from ~100 to ~850 ft (Collins, 1994f, 1995k). Smaller fault blocks lie within the larger fault blocks, and many smaller faults having throws ranging from 1 to 100 ft cut strata across the fault zone. These series of closely spaced en echelon large faults that bound the large fault blocks consist of individual fault strands that are commonly between 6 and 16 mi long. Maximum displacement is generally in the central part of individual fault strands, and displacement decreases laterally toward the fault tips. Some of the larger southeast-dipping faults are associated with northwest-dipping antithetic faults that bound narrow grabens ~3,000 to ~4,000 ft wide. South and southeast of the Edwards outcrop belt, many faults are inferred in the subsurface that generally have map patterns similar to those of the outcrop belt.

Other features of the regional structural framework of the Edwards aquifer are fault-related relay ramps (figs. 4 and 6). Relay ramps, also called transfer zones, are structures that can form between the tips of two en echelon normal faults dipping in the same direction (Larsen, 1988; Peacock and Sanderson, 1991, 1994). The ramp connects the hanging-wall and footwall blocks of the faults. Displacement from one fault is transferred across the relay ramp to the other fault. Because relay ramps are strained zones produced by shearing and block rotation during slip along the overlapping faults (Larsen, 1988), they may be cut by additional subsidiary cross faults that have different strikes and numerous fault and joint intersections. Some of the cross faults within relay ramps are probably release faults (Destro, 1995) that exhibit normal dip slip and form to release the bending stresses in the hanging wall of normal faults. Transfer cross faults having oblique slip may also form.

Within the Balcones Fault Zone, relay ramps of different sizes may lie between closely spaced (<1 mi) en echelon faults (Collins, 1993a), as well as between widely spaced (~6 to ~12 mi) large-displacement faults (Grimshaw, 1976; Grimshaw and Woodruff, 1986; Collins, 1995k). Grimshaw and Woodruff (1986) interpreted a 6-mi-wide left step (off northeast edge of map) of the outcrop belt at San Marcos to be a northeast-dipping ramp structure (San Marcos ramp) between large-displacement faults. In northwest San Antonio, the fault zone and the Edwards outcrop belt have an ~8-mi right step of the largest displacement faults and a southwest-dipping relay ramp (San Antonio ramp) that has formed between the large faults (fig. 4). Stratal folding within the San Marcos and San Antonio ramps may be enhanced because both ramps lie along the gently dipping flanks of the broad, northwest-trending San Marcos Platform. In northern Medina County an ~12-mi right step of the Edwards outcrop belt marks another relay ramp (Medina County ramp). The Medina County ramp (fig. 4) appears to be composed of at least three smaller ~4-mi-wide relay ramps.

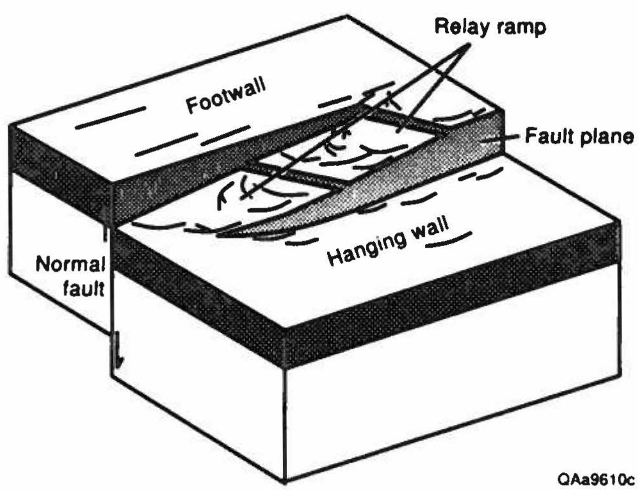

FIGURE 6. Schematic block diagram of relay ramp (modified from Peacock and Sanderson, 1994, and from Hovorka and others, 1995). Folded aquifer strata in ramp might be fractured and faulted and serve as highly transmissive pathways where offset on major faults has otherwise reduced aquifer continuity.

Summary

Normal faults and related gentle folds of the Balcones Fault Zone are the main structural control on Edwards strata and associated limestones that compose the Edwards aquifer. The confined part of the aquifer, as wide as ~30 mi in Medina County, has as much as 1,850 ft of cumulative structural relief caused primarily by Balcones faulting. In contrast, in Comal County the confined aquifer is mostly <1 mi wide, and the structural relief of the Edwards strata across the outcrop belt (≤20-mi-wide unconfined aquifer) to the interface between fresh and saline water in the Edwards subcrop is ~1,000 ft.

Faults generally strike N40° to 70°E and dip southeastward. Fewer faults dip northwestward. Subsidiary faults strike northwestward, northward, and eastward. The largest faults have throws of >800 ft, although smaller displacement faults are more common. Faulting is not uniform throughout the aquifer; detailed studies within the Edwards outcrop belt in Comal, Bexar, and eastern Medina Counties have, however, determined that the fault zone consists of several large 2- to 7-mi-wide fault blocks bounded by faults having throws between ~100 and ~850 ft. Smaller fault blocks and faults lie within the larger fault blocks.

Relay ramps represent areas within the fault zone where aquifer continuity is relatively good because strata are more continuous in ramp steps between faults than across faults and because the small faults having multiple strikes within ramps may have numerous intersections. Large, ~6- to ~12-mi-wide relay ramps are associated with en echelon faults of the Balcones zone. These large ramps formed between the tips of large-displacement en echelon faults. The ramps are cut by additional smaller faults. Smaller ramp structures having widths of <1 mi exist between more closely spaced, smaller en echelon faults.

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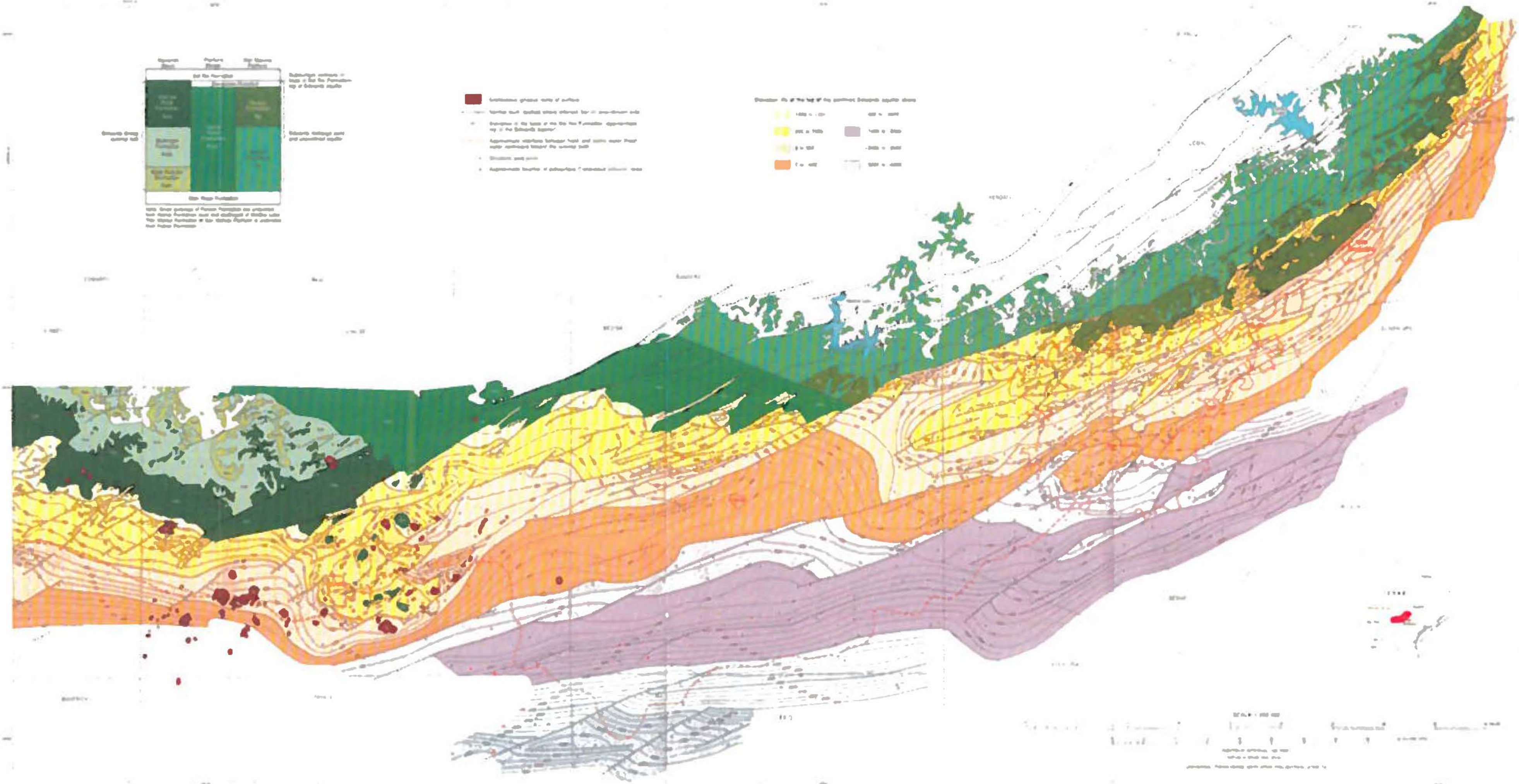

STRUCTURE MAP OF THE SAN ANTONIO SEGMENT OF THE EDWARDS AQUIFER AND BALCONES FAULT ZONE, SOUTH-CENTRAL TEXAS: STRUCTURAL FRAMEWORK OF A MAJOR LIMESTONE AQUIFER: KINNEY, UVALDE, MEDINA, BEXAR, COMAL, AND HAYS COUNTIES

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1997