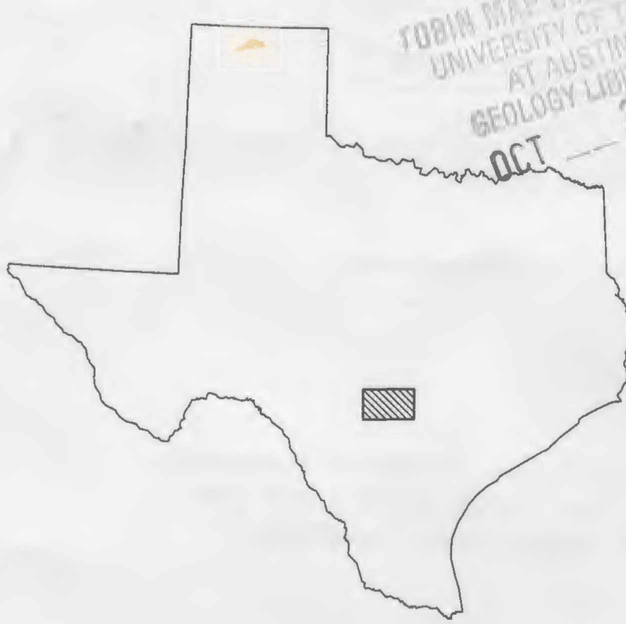
MISCELLANEOUS MAP NO. 39

Geologic Map of the New Braunfels, Texas, 30 × 60 Minute Quadrangle: Geologic Framework of an Urban-Growth Corridor along the Edwards Aquifer, South-Central Texas

1:100,000

map + text

EDWARD W. COLLINS



2000

BUREAU OF ECONOMIC GEOLOGY
Scott W. Tinker, Director
The University of Texas at Austin
Austin, Texas 78713-8924

In cooperation with the STATEMAP component of the
National Cooperative Geologic Mapping Program,
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Abstract

A map illustrating the geology of the New Braunfels, Texas, 30 × 60 minute quadrangle and this summary report present the physical geology of a rapidly growing urban-growth corridor in South-Central Texas. The map area includes a complex part of the Balcones Fault Zone and part of the regionally important recharge zone of the Edwards aquifer. The map was constructed by means of field mapping, interpretation of aerial photographs, review of existing maps and reports, and digitization of map data.

The Balcones Fault Zone, marking the northwest edge of the Texas coastal plain, is the main structural control on the geologic units. It is composed of en echelon normal faults that strike mostly N40°–70°E and dip southeastward, although a few of these dip toward the northwest. Subsidiary faults strike northwestward, northward, and eastward. In general, faults have formed multiple 2.2- to 7-mi-wide fault blocks that are bound by a long series of closely spaced, en echelon, large normal faults that have offsets ranging between approximately 100 and 850 ft. Smaller fault blocks also occur within the larger fault blocks. Many smaller faults have displacements of less than 1 to 100 ft.

Cretaceous limestone, dolomitic limestone, argillaceous limestone, marl, shale, and claystone to mudstone crop out in the map area. These rocks represent greater than 2,000 ft of shelf deposition. The Balcones Escarpment, a prominent fault-line scarp, divides the map area into a relatively high-relief physiographic area of dissected hills and steep canyons to the northwest and a low-relief area of rolling terrain to the southeast. Northwest of the Balcones Escarpment the outcrop belt consists mostly of cyclic, shallow, subtidal to tidal-flat limestones, dolomitic limestones, dolomite, and argillaceous limestones of the Glen Rose Formation and the younger Edwards Group. Siliciclastic-rich limestones of the Hensell and Cow Creek Formations crop out beneath the Glen Rose Formation locally along the Guadalupe River. Open shelf and shelf–prodelta strata that overlie the Edwards Group comprise Georgetown limestone (locally absent); Del Rio claystone to mudstone; Eagle Ford shale, mudstone, siltstone, and flaggy limestone; and Austin chalk and limestone.

Southeast of the Balcones Escarpment, poorly exposed shelf limestone, argillaceous limestone, marl, and claystone to mudstone of the Cretaceous Taylor and Navarro Groups and lower Tertiary Midway Group make up much of the outcrop belt. The Taylor, Navarro, and Midway units are commonly covered by Quaternary sand and gravel of the Leona Formation, locally deposited older (Pliocene–Pleistocene) gravel, and younger sand and gravel of terraces of main drainageways.

The map of the New Braunfels, Texas, quadrangle is intended for a diverse audience having a wide range of interests and varying knowledge of geology—including geologists, hydrologists, engineers, urban planners, archeologists, students, and laypersons. Basic geological data presented concerning faults and the limestone and dolomitic limestone that compose the Edwards aquifer are useful in water-management issues, such as groundwater flow and aquifer response for pumpage and recharge. Geological information is also important in land-use decisions, such as locating landfills and other waste-disposal sites, planning construction projects, designing foundations, and meeting demands for construction materials.

Keywords: Balcones Fault Zone, Cretaceous stratigraphy, Edwards aquifer, environmental and urban geology, geologic map, South-Central Texas

Introduction

This report describes the physical geology of a South-Central Texas area that is undergoing rapid urban growth. The study area encompasses north San Antonio, Lake Medina, Comfort, Wimberley, Canyon Lake, and New Braunfels, and it includes parts or all of Bexar, Comal, Guadalupe, Medina, Kendall, southwestern Hays, southern Blanco, eastern Bandera, and eastern Kerr Counties (fig. 1 and map). The study area includes part of the regionally important Edwards aquifer and recharge zone, a complex part of the Balcones Fault Zone, and the east margin of the Edwards Plateau.

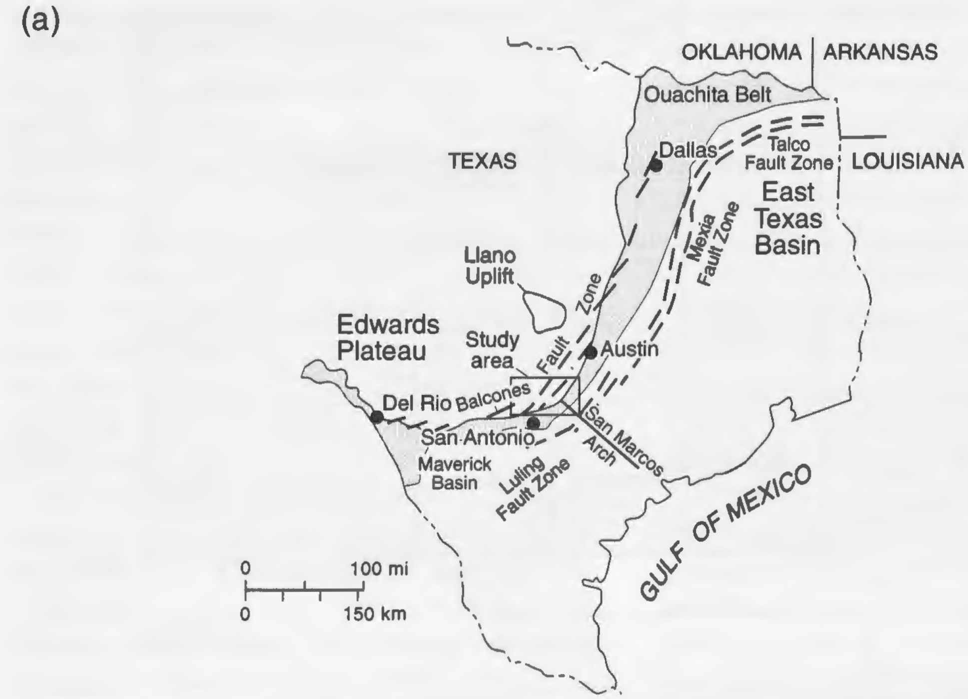
An objective of this report is to provide basic geologic information on the 1:100,000-scale geologic map constructed for this study (map), which, in turn, is a useful source of geological information on the South-Central Texas urban-growth corridor. Information provided by the map and this report is intended for a diverse audience comprising professionals in geology, hydrology, engineering, urban planning, archeology, and related fields, as well as laypersons and students, all who have varying levels of knowledge of geology.

The geologic structure and stratigraphy of this region figure prominently in geologists' and other professionals' planning of land use, designing of construction projects, and managing of the Edwards aquifer. The physical properties of the different lithostratigraphic units, for example, may influence construction and urban-development practices. Some strata can be excavated more easily than others, affecting the cost of construction projects. Stable foundations and efficient septic tanks are easier to construct in some units than in others because of the range of physical and lithologic properties of the units. Clay-rich units and limestone strata overlying clay-rich strata along slopes are more likely to slump or slide than are some of the thicker limestone units. In addition, faults can locally juxtapose strata having different physical properties, creating potential construction and foundation problems. Faults are the principal structural control on the Edwards aquifer and recharge zone. Karst features such as sinkholes and caves, as well as some faults and joints, form local and regional ground-water conduits. Such features are particularly important in recharge of the Edwards aquifer. Some large faults may also act as barriers or partial barriers to ground-water flow.

Structural attributes, including fault location, length, dip, and amount of displacement of normal faults of the Balcones Fault Zone, which cut across the study area, are described in this report. Also discussed herein are characteristics of the physical stratigraphy, including lithology, thickness, and occurrence. This report provides general information relating geology to aspects of land use, urban planning, construction practices, and water-resource management.

Methods

This study consisted of (1) review and compilation of existing geologic literature and interpretation concerning the area, (2) study and interpretation of aerial photographs, (3) identification of the lithostratigraphic units and faults that cut the units at accessible localities in the field, and (4) preparation of geologic maps. Thirty-two open-file geologic maps (fig. 2), scale 1:24,000, were constructed of the study area between 1990 and 1995 according to standard geologic field techniques. Compilation and field review of existing geologic maps of various scales aided map interpretation. Photographs used in this study included (1) 1:80,000-scale, black-and-white, 1983 National High Altitude Program (NHAP) photography; (2) 1:40,000-scale, false-color-infrared, 1983 National Aerial Photograph Program (NAPP) photography; and (3) 1:62,000-scale, black-and-white, 1953 Army Mapping Service photography. Photographs were viewed in stereo, and



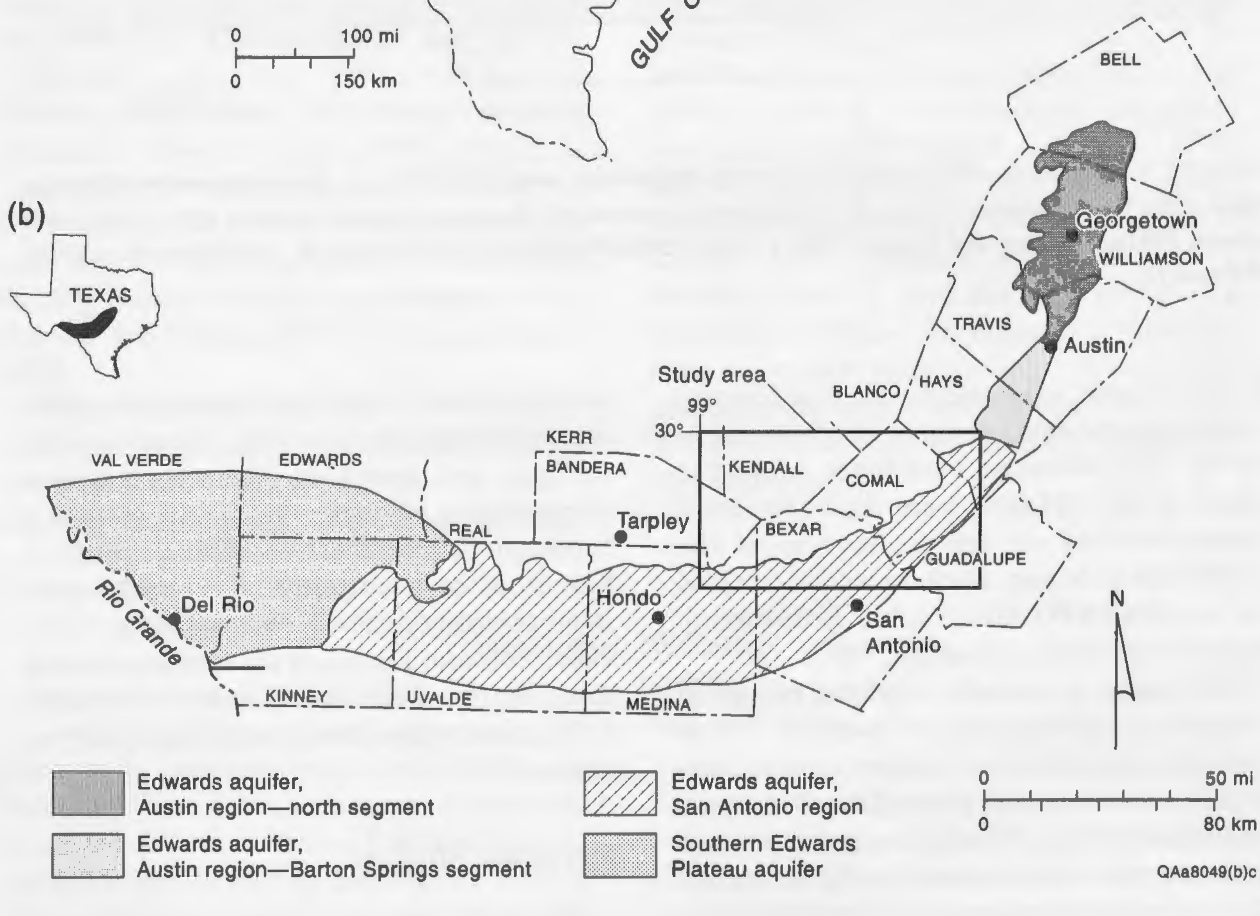


FIGURE 1. (a) Regional setting of study area. Map area is within regional Balcones Fault Zone. Northwest map area coincides with east edge of Edwards Plateau. East part of study area is on the San Marcos Arch. During deposition of Cretaceous rocks the arch was a platform (called the San Marcos Platform) located between the East Texas Basin and the Maverick Basin. (b) Diagram showing Edwards aquifer coinciding with the map area.

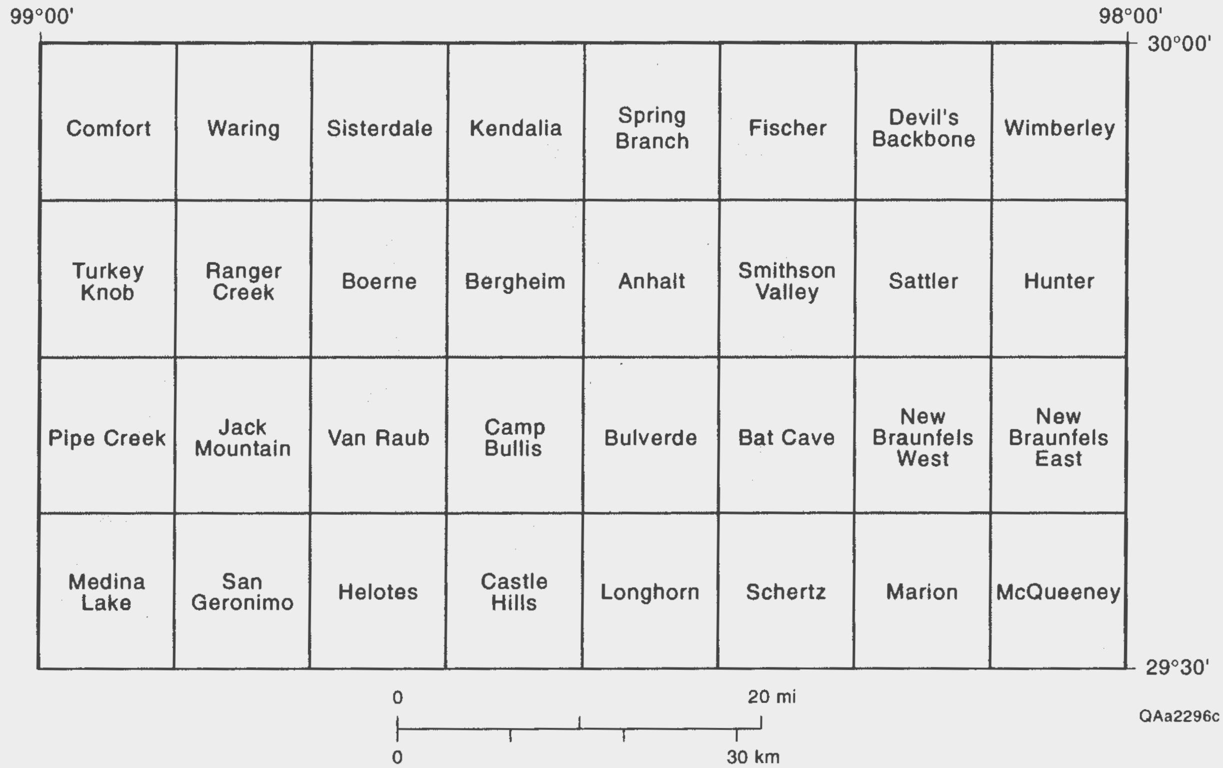


FIGURE 2. Diagram showing locations of 32 open-file geologic maps, 1:24,000 scale, that compose the "Geologic Map of the New Braunfels, Texas, 30 × 60 Minute Quadrangle" (Baumgardner and Collins, 1991; Collins and others, 1991a, b; Raney and Collins, 1991; Collins, 1992a through d, 1993b through h, 1994a through e, 1995a through j).

a zoom transfer scope was used to transfer some of the geologic data viewed on the photographs to the 1:24,000-scale base maps. Open-file maps, scale 1:24,000, were digitized into a seamless data set for production of the 1:100,000-scale map. Digital-map data are also in an ARCINFO Geographic Information System (Tremblay and others, 1997).

The region is generally vegetated enough to make mapping difficult, and public access is typically limited to public roads, public areas at lake shorelines, and parts of the Guadalupe and Blanco Rivers. Geologic unit contacts and faults are portrayed on maps by solid and dashed lines to reflect the relative certainty with which features can be located in the field and observed on aerial photographs. Unit contacts and faults drawn as solid lines are relatively more distinct in the field and on photographs than those drawn as dashed lines. Dotted lines show where faults are covered by alluvium. The contact between the upper and lower Glen Rose units is dashed everywhere because it is an informal subdivision. Identification of this contact is based on the occurrence of a stratigraphic interval having thin beds that contain the fossil clam, *Corbula*. The top of the *Corbula* interval marks the top of the lower Glen Rose. The letter C designates where these fossils were observed in the field.

Previous Studies

This study benefited from, and builds on, many previous geologic investigations done within and near the study area. Several regional geologic maps, scales of 1:250,000 or 1:500,000, illustrate the study area's setting

(U.S. Geological Survey, 1937; Brown and others, 1974; Gustavson and Wermund, 1985; Barnes, 1992). Other existing geologic maps having scales between 1:24,000 and 1:250,000 illustrate parts of the study area in varying detail and accuracy (Liddle, 1918; Sellards, 1919; George, 1952; Bills, 1957; King, 1957; Noyes, 1957; Whitney, 1957; Arnow, 1959; Holt, 1959; Reeves and Lee, 1962; DeCook, 1963; Cooper, 1964; Abbott, 1966, 1973; Grimshaw, 1970, 1976; Newcomb, 1971; Rose, 1972; Shaw, 1974; Waddell, 1977; Waterreus, 1992; and Stein, 1993). Most of these maps are presented on planimetric base maps. Some of these previous maps were done for Master's and Ph.D. studies and are unpublished.

The map was constructed from 32 geologic maps, scale 1:24,000, interpreted by the author and coworkers (Baumgardner and Collins, 1991; Collins and others, 1991a, b; Raney and Collins, 1991; Collins, 1992a through d, 1993b through h, 1994a through e, 1995a through j). Independent of the mapping for this report, the U.S. Geological Survey mapped hydrologic units of the Edwards aquifer as part of individual county studies (Small and Hanson, 1994; Hanson and Small, 1995; Stein and Ozuna, 1995).

Many of the numerous previous studies concerning geologic aspects of the study area are mentioned later in this report. A few of the key stratigraphic investigations include a discussion by Young (1967) of the Lower Cretaceous and the Young and Woodruff (1985) guidebook of the Upper Cretaceous Austin Group; the Rodda and others (1966) study of Lower Cretaceous rocks; the Stricklin and others (1971) and Amsbury (1974) investigations of the Lower Cretaceous Trinity deposits; interpretations of the Lower Cretaceous Edwards Group by Fisher and Rodda (1969), Rose (1972), and Abbott (1973); and the Moore (1964; 1996) evaluations of Fredericksburg strata. The McFarlan and Menes (1991) summary of the Lower Cretaceous of the Gulf of Mexico Basin and the Sohl and others (1991) discussion of the Upper Cretaceous of the Gulf of Mexico Basin were also useful, as was the Sellards and others (1932) volume on the stratigraphy of Texas and the Roy (1986) summary of the Mesozoic geology of the region. Regional faulting of the area was summarized recently by Collins and Hovorka (1997), and hydrology of the region was summarized by Klempt and others (1979) and Maclay and Small (1986). Relationships between geology and land use in parts of Bexar County were discussed by Shaw (1974), Waddell (1977), and Ewing (1996). An informative volume that contains a variety of articles concerning geology, hydrology, ecology, and social development along the Balcones Escarpment was edited by Abbott and Woodruff (1986).

Geologic Setting

Geology of the map area is dominated by Cretaceous carbonate rocks and the Tertiary Balcones Fault Zone. Cretaceous strata were deposited on the San Marcos Platform, a southeastern platform area of the broader Central Texas Platform between the East Texas and Maverick Basins (fig. 1; map). Cretaceous units exhibit facies changes and thickness increases from the positive platform area toward the more rapidly subsiding basin areas (Rose, 1972). North of the study area is the Llano Uplift, a part of the Texas craton Precambrian basement. Precambrian rocks of the Llano Uplift region were exposed as islands during Early Cretaceous time, but they were submerged before the Late Cretaceous began.

Normal faults of the Balcones Fault Zone generally follow the regional strike of the Cretaceous outcrop belt and the structural grain of the buried Paleozoic Ouachita fold and thrust belt (Sellards and Baker, 1934; Weeks, 1945; Flawn and others, 1961; Murray, 1961; Caran and others, 1981; Ewing, 1991a, b). 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 movement on the Balcones Fault Zone is thought to have occurred during late Oligocene or early Miocene (Weeks, 1945).

Structure

Faults

In the map area, faults of the Balcones Zone have formed multiple 2.2- to 7-mi-wide fault blocks bounded by a long series of southeast-dipping, closely spaced, en echelon, normal faults that have throws ranging between approximately 100 and 850 ft (map, cross section A–A′). Smaller fault blocks occur within the larger fault blocks, and many smaller faults having throws ranging from less than 1 to 100 ft cut strata across the fault zone. Series of closely spaced, en echelon faults that bound the large fault blocks consist of individual fault strands that are commonly between 6 and 16 mi long. Spacing between the large faults increases away from the largest displacement fault that occurs at the Balcones Escarpment. Some of the larger faults, displaying between 340 and 850 ft of throw, are associated with northwest-dipping antithetic faults that bound graben that are 3,000 to 4,000 ft wide (Collins, 1993a, 1994f, 1995k; Collins and Hovorka, 1997).

Faults strike mostly N40°–70°E and dip southeastward. Fewer faults dip northwestward. Subsidiary faults strike northwestward, northward, and eastward. Rare outcrops containing larger faults indicate that fault surfaces, which are irregular, have dips between 50° and 85° and display slickenlines that are 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°). Local small faults displaying minor oblique slip possibly result from local block rotations or local stress-field variations during the faulting.

Across the fault zone, the composite offset of the faults has caused more than 1,200 ft of structural relief on strata. For individual fault strands, the maximum displacement is generally in the central part of the fault, and offset decreases horizontally toward the fault tips. The two largest faults in the map area have between 500 and 800 ft of throw at the central parts of the faults. Both of these faults exhibit distinct fault-line scarps that have topographic relief commonly between 50 and 100 ft. One of these faults crosses through New Braunfels (map), and the other fault crosses through the Haby Crossing area at the Medina River and through Helotes.

San Antonio Relay Ramp

The San Antonio relay ramp is a gentle, southwest-dipping monocline, formed between the tips of two en echelon master faults having maximum throws of as much as 800 ft (fig. 3b). At relay ramps, also called transfer zones, displacement from one fault is transferred across the ramp to the other fault (Larsen, 1988; Peacock and Sanderson, 1991, 1994). The ramp connects the hanging-wall and footwall blocks of the faults.

The San Antonio relay ramp is defined by an approximately 8-mi-wide right step of the Kainer and Person Formations outcrop belt and

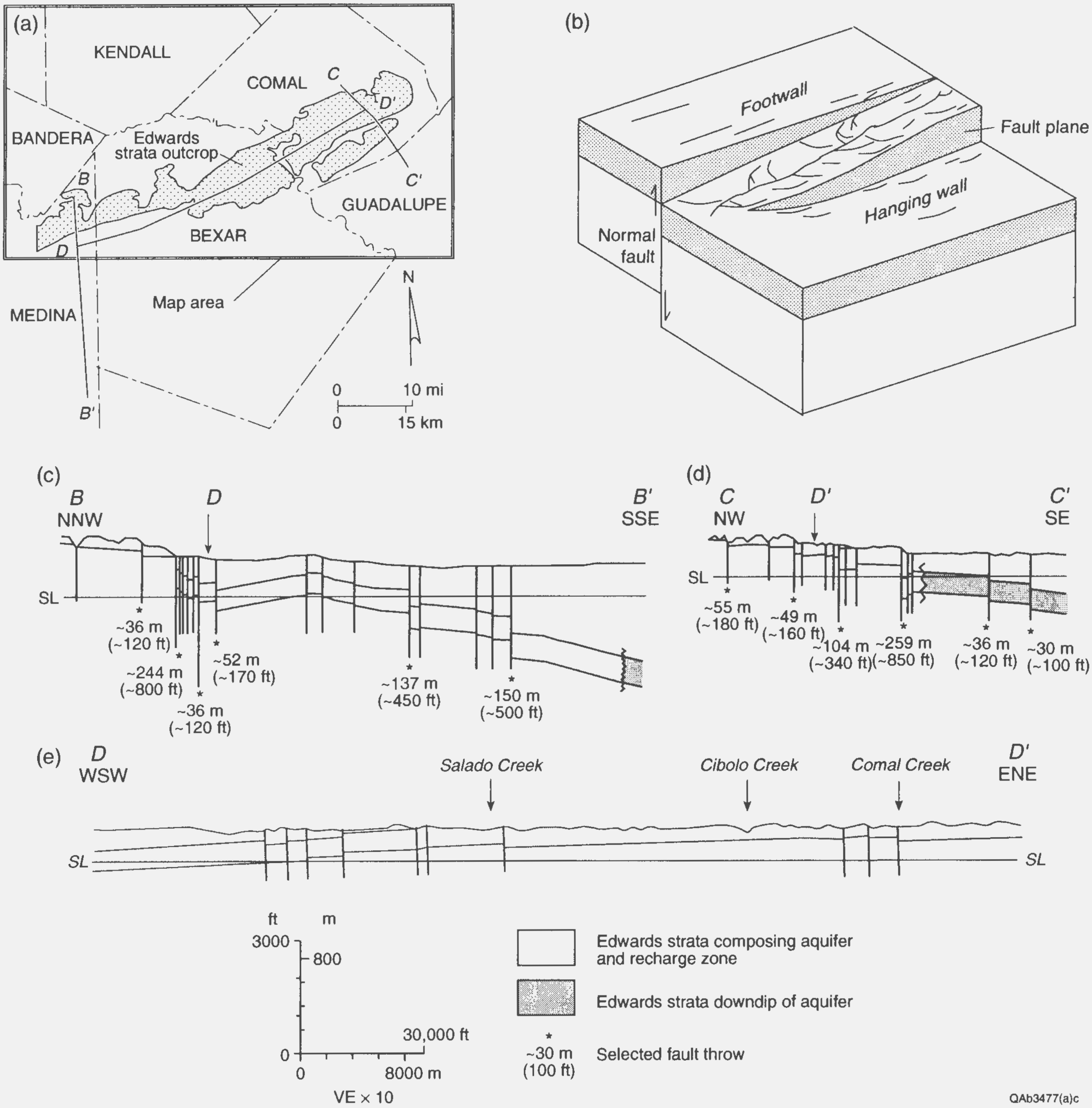


FIGURE 3. (a) Location of Edwards strata cross sections; (b) schematic block diagram of relay ramp (folded aquifer strata in ramp are highly fractured locally and may serve as a highly transmissive pathway); (c) and (d) structural cross sections of Edwards strata cut by master faults of the San Antonio relay ramp; and (e) structural cross section along axis of relay ramp.

the large en echelon master faults that bound the ramp (fig. 3b). The master faults strike N55°–75°E, and maximum displacement exceeds the approximately 550 ft thickness of the Kainer and Person Formations. Within the ramp, tilted strata dip gently southwestward at about 25 ft/mi, and the strata are cut by smaller faults that have displacements of between less than 1 and 500 ft. The total structural relief along the ramp's southwest-trending axis is between 750 and 800 ft. The ramp's internal framework is defined by three fault blocks between 3 and 4 mi wide that are bound by northeast-striking faults having maximum throws of between 100 and 500 ft. Structures like the San Antonio relay ramp are important to Edwards aquifer recharge and ground-water management because the ramp is an area of relatively good stratal continuity linking the outcrop-belt recharge zone and unconfined aquifer with the downdip confined aquifer. Part of the San Antonio relay ramp, lying within the aquifer recharge zone (Kainer and Person Formations outcrop belt), is crossed by several southeast-draining creeks (including Salado, Cibolo, and Dry Comal Creeks) that supply water to the ramp recharge area.

Lithostratigraphy

Strata of the map area (fig. 4) are mostly Cretaceous limestone, dolomitic limestone, dolomite, argillaceous limestone, marl, and mudstone that represent more than 2,000 ft of shelf deposition on the southeast-trending San Marcos Platform. Northwest of the Balcones Escarpment, the outcrop belt consists mostly of cyclic, shallow, subtidal to tidal-flat limestones, dolomitic limestones, and dolomite of the Glen Rose Formation and the Kainer and Person Formations of the Edwards Group. Older, nearshore, siliciclastic-rich limestones and marl of the Hensell and Cow Creek Formations crop out beneath the Glen Rose Limestone locally along the Guadalupe River at the west margin of the fault zone. Open-shelf limestones and shelf–prodelta shale and mudstone that overlie the Edwards Group compose Georgetown limestone (possibly absent locally), Del Rio claystone to mudstone, Buda limestone, Eagle Ford shale, mudstone, and siltstone, and Austin chalk and limestone. These post-Edwards deposits crop out within grabens west of the escarpment, as well as locally along the escarpment. Southeast of the escarpment, poorly exposed shelf marls, argillaceous limestones, and claystone to mudstone of the Taylor Group make up much of the Cretaceous outcrop belt. These Cretaceous units are commonly covered by Quaternary sand and gravel of the Leona Formation, local older Pliocene to Pleistocene gravel, and younger sand and gravel of terraces of main drainageways. Also in the southeast part of the study area are Cretaceous Navarro and Eocene Midway claystone and shale and sandier Eocene Wilcox sandstone, siltstone, and mudstone.

Lower Cretaceous

Lower Cretaceous rocks of the study area were deposited mostly in marine platform environments (fig. 5). Moore (1996) reported that the Lower Cretaceous of Central Texas consists of eight intervals of cyclic deposition that are third-order stratigraphic sequences. The focus of this report deals with basic lithologic and physical characteristics of the lithostratigraphic units. In line with international usage, the Lower and Upper Cretaceous boundary of this study is thought to be at the base of the Del Rio Formation (McFarlon and Menes, 1991). Some previous researchers postulated that a Buda–Eagle Ford unconformity, which formed at the end of widespread Buda carbonate

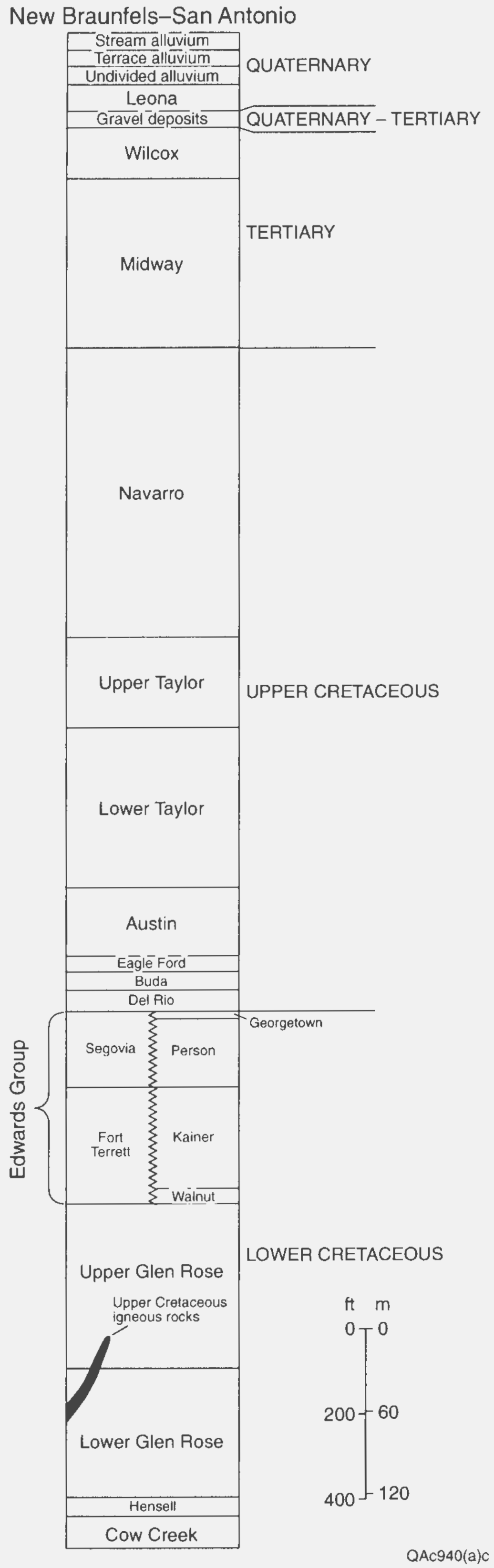


FIGURE 4. Lithostratigraphy of study area.

deposition and before abundant Eagle Ford terrigenous clastic deposition (fig. 4), represents the boundary between the Lower and Upper Cretaceous within the Gulf Coast of Texas (Young, 1967; Brown and others, 1974).

Cow Creek Formation

About 50 ft of Cow Creek limestone and argillaceous limestone crops out locally along the Guadalupe River and some of its tributaries (Cooper, 1964). The base of the Cow Creek does not crop out, although George (1952) estimated on the basis of drilling interpretations a total thickness of approximately 75 ft. The lower part of this unit is a poorly indurated, clay-rich limestone having sandy and dolomitic intervals and abundant burrows locally. These lower Cow Creek strata form gentle slopes along the drainageways but may also form the steep undercut part of bluffs at river cutbanks. The upper limestone part of this unit is well-indurated, grainy rock that has massive to thick beds. Upper Cow Creek limestone commonly forms a distinct ledge along the river. Fossiliferous and crossbedded, it contains some siliceous nodules, and the upper surface contains limonite nodules and poorly defined borings. Cow Creek strata were deposited in a nearshore marine and, possibly, beach environment (Cooper, 1964). Stricklin and others (1971) reported that upper Cow Creek strata located north of the map area in northern Blanco and western Travis Counties represent an offlapping sequence of beach deposits built out from a regressing shoreline. In this region north of the study area, Cow Creek deposits are disconformably overlain by nonmarine Hensell terrigenous clastic deposits. Cooper (1964) reported that Cow Creek and overlying Hensell deposits along the Guadalupe River in the study area represent deposition in a setting farther offshore, where Cow Creek marine deposition was followed first by a hiatus and then Hensell marine deposition.

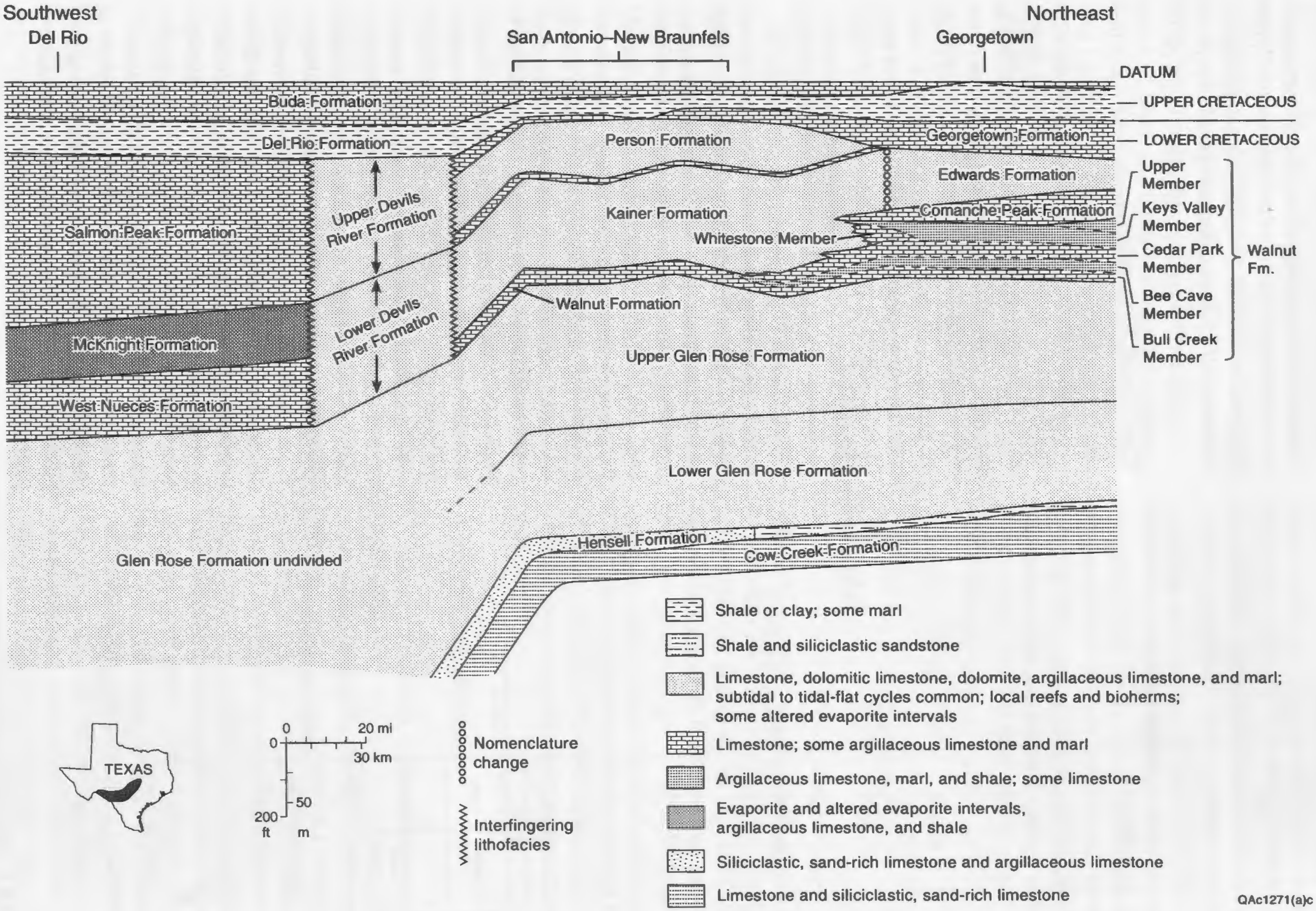


FIGURE 5. Southwest-northeast diagrammatic correlation of Lower Cretaceous units across South-Central Texas and the study area. Synthesized from many previous studies cited in text. General lithologies shown.

Hensell Formation

Sandy limestone and sandy dolomitic limestone compose the approximately 45-ft-thick Hensell Formation exposed along the Guadalupe River (map) and its tributaries (Cooper, 1964). The lower part of the Hensell outcrop is sandy limestone and sandy dolomitic limestone that contains terrigenous siliciclastic sand (Cooper, 1964). This part of the unit, which is poorly indurated, locally contains calcareous geodes and oysters. Glauconitic sandy limestone defines the upper part of the unit. The lower part weathers more easily than the upper part, and the lower part generally supports grass vegetation and weathers to a loose, yellowish-brown soil. The outcrop belt of the lower Hensell also contains cultivated and previously cultivated fields. Vegetation contrasts between the lower Hensell and the overlying and underlying strata, which support denser tree growth, can commonly be used to identify its areal distribution.

Hensell deposits in the map area were deposited in a nearshore marine environment, although updip toward the north and northwest, Hensell sediments were deposited in an alluvial setting (Cooper, 1964; Stricklin and others, 1971). Regionally Hensell deposits thin downdip by laterally grading and interfingering into marine Glen Rose deposits.

Glen Rose Formation

Limestone, dolomitic limestone, argillaceous limestone, and some marl compose the Glen Rose Formation. These strata are divided into lower and upper units by a regionally extensive stratigraphic interval that includes a fossiliferous nodular limestone containing the echinoid *Salenia texana*. This *Salenia texana* zone of the lower Glen Rose is overlain by an interval that has one to three thin limestone beds containing the abundant casts and steinkerns of the small clam *Corbula* (Stricklin and others, 1971; Stricklin and Amsbury, 1974; Pittman, 1989). An interval of weathered evaporitic strata overlies the *Corbula* interval, although evaporite minerals are not seen at the surface because of dissolution. The top of the *Corbula* interval marks the top of the lower Glen Rose.

Characteristic Glen Rose stair-step topography caused by alternating resistant and recessive beds results from the common, upward-shoaling, subtidal to tidal-flat, cyclic deposition that occurred (Stricklin and others, 1971; Moore and Bebout, 1989). Fossils include mollusks, rudistids, oysters, and echinoids. The foraminifer, *Orbitolina*, is common, and dinosaur tracks have been found locally (Jones and others, 1998). Some strata exhibit honeycomb porosity and karst features, including sinkholes and caves.

The 200- to 270-ft-thick lower Glen Rose has massive beds locally and contains some rudistid reefs and mounds (Stricklin and others, 1971; Perkins, 1974). Upper Glen Rose strata are more dolomitic and less fossiliferous than they are in the lower Glen Rose. Two intervals of disturbed bedding and collapse breccia probably caused by evaporite dissolution occur in the upper Glen Rose. Thickness of the upper Glen Rose is approximately 400 ft.

Recent soil studies within Glen Rose terrain indicate that soils overlying some of the limestone beds are degraded and nearly impervious, whereas other soils overlying more argillaceous beds are thicker and have greater water-infiltration and water-holding properties (Marsh and Marsh, 1994; Woodruff and others, 1994; Wilding, 1997). These investigations suggest that soil analyses done in conjunction with geological interpretations may aid engineers and developers in land-use practices and planning.

Walnut Formation

Walnut limestone, marl, and dolomitic limestone compose a thin, 30- to 50-ft-thick unit that thickens toward the north-northeast away from the study area (Moore, 1964). Some earlier workers, including Rodda and others (1966), Newcomb (1971), Abbot (1973), Shaw (1974), and Waddell (1977), mapped Walnut strata along the Balcones Fault Zone in Bexar, Comal, and Hays Counties. Other previous workers (Rose, 1972; Maclay and Small, 1986) included this thin unit with the Kainer Formation (lower Edwards Group). These rocks are sometimes referred to as the nodular member of the Edwards aquifer (Maclay and Small, 1986; Small and Hanson, 1994; Hanson and Small, 1995; and Stein and Ozuna, 1995). Walnut strata mapped in the Balcones Fault Zone–San Marcos Platform study area are stratigraphically equivalent to the Rose (1972) basal nodular member, the lower strata of the Fort Terrett Formation at the east margin of the Edwards Plateau (Abbott, 1973).

Two members of the Walnut Formation, the Bull Creek and Bee Cave, were recognized in southwest Hays County in the Wimberley area by Moore (1964) and Grimshaw (1970). The younger Bee Cave contains argillaceous limestone, marl, and some limestone, and the older Bull Creek comprises limestone and dolomitic limestone interbedded with some argillaceous limestone and marl. *Exogyra texana* is a diagnostic fossil oyster in the unit. Some honeycomb porosity exists.

In areas southwest of Wimberley, the Walnut Formation has not been divided (Newcomb, 1971; Abbott, 1973; Shaw, 1974; Waddell, 1977). Walnut strata are also undivided on the map for this study. Abbott (1973) identified Bee Cave and Bull Creek lithologies in an undivided Walnut Formation throughout the Balcones Fault Zone and reported that the unit is a useful, distinctive marker horizon throughout the area. Contact with the underlying Glen Rose Formation is gradational. Abbott (1973) interpreted the Glen Rose–Walnut contact to represent a genetic change from hypersaline upper Glen Rose deposits to normal marine or brackish-water Walnut deposits. Northwest of the study area near Fredericksburg, Moore (1996) interpreted the Fort Terrett Formation (lower Edwards Group of the Edwards Plateau) to overlie the Cedar Park nodular limestone, a younger member of the Walnut. He also interpreted the Bull Creek and Bee Cave to onlap and pinch out against the underlying Glen Rose Formation.

Edwards Group

Edwards cyclic shallow-water carbonate rocks along the Balcones Fault Zone in the San Marcos Platform region have been subdivided into two formations, the Kainer and Person Formations (Rose, 1972; Abbott, 1973). These strata grade into cyclic platform-margin deposits of the Devils River Formation west of the map area (Smith, 1964; Rose, 1972, 1974). Rose (1972, 1974) documented that Kainer and Person strata are approximately equivalent to the Fort Terrett and Segovia Formations of the Edwards Plateau. He interpreted marly, argillaceous limestone of the lower Segovia to grade eastward into the grain-rich upper part of the Kainer and the argillaceous, regional dense member of the lower Person Formation (Rose, 1972, 1974). For this study, the Edwards Group nomenclature change from Kainer and Person Formations to Fort Terrett and Segovia Formations, respectively, corresponds to the transition from the Balcones Fault Zone–San Marcos Platform area to the Edwards Plateau. This nomenclature change is illustrated on the accompanying map at locations chosen for nomenclature convenience. Edwards Group nomenclature for the Balcones Fault Zone–San Marcos Platform and Edwards Plateau areas is well established (Rose, 1972; Abbott, 1973), although the precise boundaries for nomenclature change have not been defined.

On the San Marcos Platform along the fault zone (Kainer and Person Formations), the Edwards outcrop-belt nomenclature was extended from subsurface nomenclature, where informal unit members were also identified (Rose, 1972; Abbott, 1973). Members of the Kainer include (1) the Basal Nodular Member, which is equivalent to the Walnut strata mapped in the study area; (2) the Dolomitic Member; (3) the Kirschberg Evaporite Member; and (4) the Grainstone Member. Person rocks have been subdivided into (from oldest to youngest) (1) the Regional Dense Member; (2) the Leached and Collapsed Members, undivided; and (3) the Cyclic and Marine Members, undivided (Rose, 1972; Maclay and Small, 1986).

Abbott (1973) noted that recognition of the Edwards members in outcrop is difficult because the stratigraphic position of the strata is complicated by faulting. He also determined that because the rocks have commonly been dolomitized, chertified, recrystallized, and dedolomitized, they have lost some of the unique characteristics typical of different depositional facies. Hovorka (1996) pointed out that the repetitiveness of cycles in the Edwards Group can also be a hindrance to understanding the stratigraphy in outcrop because repetition of the similar lithologies in the stacked cycles makes it more difficult to accurately determine stratigraphic position from small or discontinuous outcrops. Abbott (1973) reported that the Dolomitic, lower Grainstone, Leached, Marine, and Cyclic Members of the Kainer and Person Formations are unrecognizable in the outcrop belt individually. Because the lower Person's Regional Dense Member is in conjunction with adjacent stacked grainstones of the upper Kainer Formation below, it is commonly recognizable in outcrops. The lower nodular member, equivalent to Walnut strata for this study, and the underlying Glen Rose rocks are also generally distinct enough to be recognized in outcrops. Hovorka (1996) noted that if multiple cycles can be identified in measured sections of outcrops and core, then recognition of well-developed stacking patterns in the formation sequences can be used to help correlate the strata.

Woodruff and others (1998) recently noted that nomenclature of Edwards Group subdivisions can be confusing to the general public, as well to geologists unfamiliar with Central Texas geology. They suggested using the most widely recognized name, the Edwards Limestone, for appropriate overview reports to maintain communication with the general public. Although the geologic map of the study area illustrates subdivisions of the Edwards Group, the stratigraphic columns on the map and in figure 4 help identify which units are part of the Edwards Group.

Kainer Formation

Cyclic subtidal to tidal-flat deposition resulted in much of the limestone, dolomitic limestone, and dolomite that composes the Kainer Formation, the lower unit of the Edwards Group (Rose, 1972; Abbott, 1973). This unit, approximately 250 ft thick in outcrop, thickens downdip toward the southeast. Grainstones and packstones are abundant in the upper part of the unit. In some places leached evaporitic strata and breccias are very distinct in the middle part of the unit. The lower part of the unit commonly comprises wackestones and packstones having local argillaceous intervals.

Chert occurs throughout the unit in varying amounts and is typically abundant. Honeycomb porosity is common. Current laminations and low-angle cross-stratification are also present. Common fossils include rudistids, oysters, gastropods, and miliolids (Rose, 1972; Abbott, 1973).

Person Formation

Person limestone, dolomitic limestone, and dolomite also reflect the shallow subtidal to tidal-flat cyclic deposition on the San Marcos Platform (Rose, 1972; Abbott, 1973). This upper unit of the Edwards Group, 130 to 150 ft thick along its outcrop belt, thickens downdip. Person outcrops typically contain limestone interbedded with recrystallized dolomitic limestone and argillaceous limestone (Rose, 1972; Abbott, 1973). Some leached and collapsed intervals exist, and honeycombed porosity is common. Pockets of red clay (terra rosa) occur locally in collapse features, cave and vuggy intervals, and solution-widened bedding planes and fractures. Chert is also locally abundant. Common fossils include pelecypods, gastropods, and rudistids. The lower 20 to 30 ft comprises the Regional Dense Member, commonly dense argillaceous limestone and limestone. The Regional Dense Member of the San Marcos Platform, stratigraphically equivalent to the Kiamichi Formation of North Central Texas (Rose, 1972; Abbott, 1973), represents a regional sea-level highstand. A distinct topographic bench commonly occurs at the Regional Dense Member's contact with the Kainer Formation, which aids in the mapping of these units.

Fort Terrett Formation

Fort Terrett limestone, dolomitic limestone, dolomite, and lesser argillaceous limestone forms the lower unit of the Edwards Group on the Edwards Plateau (Rose, 1972). Similar to time-equivalent Kainer rocks, much of the Fort Terrett strata represent cyclic, shallow, subtidal to tidal-flat deposition (Rose, 1972). Lateral lithologic changes between Kainer and Fort Terrett deposits are gradational and are related to minor facies changes. At the east margin of Edwards Plateau the Fort Terrett is about 260 ft thick. This unit's lower 20 to 40 ft of strata are mostly subtidal nodular limestone and argillaceous limestone that are approximately equivalent to the Walnut Formation of the Balcones Fault Zone area to the southeast and east (Abbott, 1973).

Segovia Formation

Segovia strata compose the upper unit of the Edwards Group at the Edwards Plateau (Rose, 1972). Only minor amounts of Segovia limestone, dolomitic limestone, dolomite, and argillaceous limestone exist in the northwest part of the map area. West-northwest of the study area on the Edwards Plateau, the unit is 360 ft thick.

Georgetown Formation

Open, marine-shelf limestone and some marl compose the Georgetown Formation (Young, 1967). Georgetown limestone, commonly argillaceous, exhibits nodular bedding. Fossils include the mollusk *Waconella wacoensis* (formerly *Kingena wacoensis*) and *Gryphaea washitaensis* (Young, 1967; Small and Hanson, 1994). The unit is thin across the San Marcos Arch, generally less than 30 ft, and may be locally absent or so thin that it is covered by overlying Del Rio float (King, 1957; Young, 1967). A disconformity exits between the Georgetown and Person Formations across the San Marcos Arch (Young, 1967).

Georgetown strata are mostly covered by vegetation and soil throughout the study area. This unit's areal surface distribution illustrated on the map is mostly inferred. It is thought to be a thin, upper part of the Edwards aquifer's strata, although it has generally lower permeabilities than do most of the Person and Kainer strata.

Upper Cretaceous

Upper Cretaceous rocks of the study area represent marine shelf deposition of seven lithostratigraphic units (in ascending order): the Del Rio, Buda, and Eagle Ford Formations and the Austin, lower Taylor, upper Taylor, and Navarro Groups (fig. 6). The Upper Cretaceous sedimentation record indicates that cyclic sea-level fluctuations affected a broad, generally low-relief shelf area (Sohl and others, 1991). Regional regression and transgression during the beginning of the Late Cretaceous resulted in deposition of Del Rio clay- and mud-rich deposits and Buda limestone. An episode of

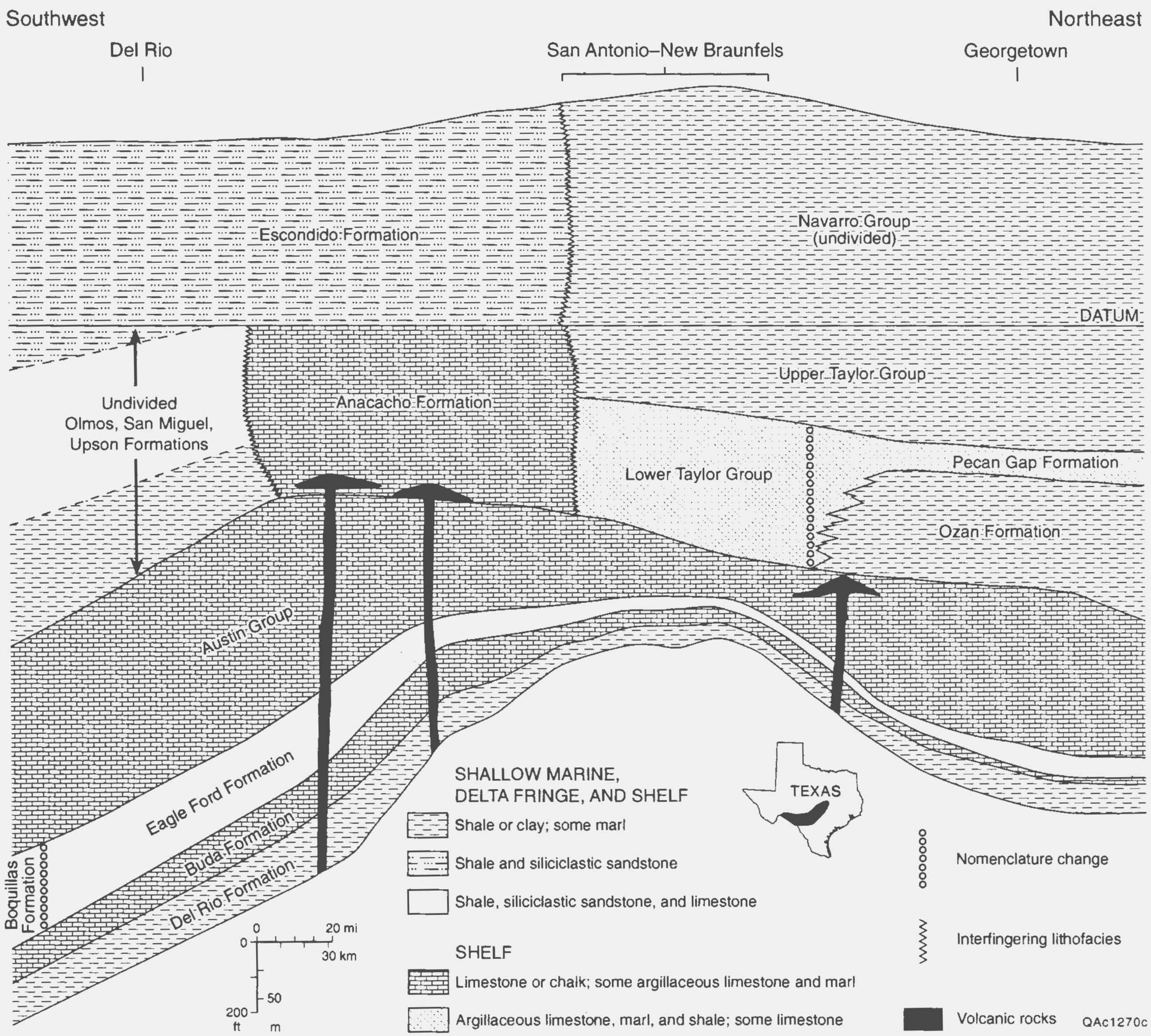


FIGURE 6. Southwest-northeast diagrammatic correlation of Upper Cretaceous units across South-Central Texas and the study area. Synthesized from many previous studies cited in text. General lithologies shown.

shelf inundation coincided with Eagle Ford shale deposition. This event was followed by a period of abundant chalk and carbonate deposition of the Austin Group. Outside the study area, the rock record indicates that Cretaceous volcanism coincided with upper Austin and lower Taylor deposition (Ewing and Caran, 1982; Sohl and others, 1991). During the later part of the period, Taylor and Navarro deposits show a gradual increase in terrigenous sediment influx.

Del Rio Formation

The Del Rio Formation consists of calcareous, fossiliferous clay–claystone to mud–mudstone that commonly contains pyrite and gypsum. Minor, thin, lenticular beds of highly calcareous siltstone may also occur. This clay-rich unit forms highly expansive soil. Fossils of *Ilymatogyra arietina* (formerly *Exogyra arietina*) are abundant (Young, 1967; Small and Hanson, 1994). Unweathered Del Rio clay is composed of kaolinite, illite, and lesser amounts of montmorillonite. During weathering, illite alters to montmorillonite. Thus, weathered Del Rio clay contains only small quantities of illite and greater amounts of montmorillonite (Garner and Young, 1976). This unit is between 15 and 50 ft thick across the study area (map).

Del Rio Formation is commonly poorly exposed in slopes below the erosionally resistant Buda Formation. Water tanks for livestock are commonly excavated in the unit because it holds water relatively well. The Del Rio also serves as the confining layer overlying the Edwards aquifer.

Buda Formation

Marine-shelf limestones compose 40 to 65 ft of the Buda Formation across the study area. Limestone in the upper part of the Buda, generally hard and dense, may exhibit conchoidal fracturing and a porcelaneous texture when broken. The lower limestones within the unit are softer and chalky. Buda rocks contain glauconite and fossils, and some beds contain abundant broken fossil fragments (Martin, 1967; Young, 1967).

Buda limestones form resistant caps on hills. On aerial photographs and in the field, the contact between the erosionally resistant Buda and easily erodible Del Rio is typically identified by a distinct break in slope. Blocks of Buda limestone commonly slump downhill into the clayey Del Rio.

Eagle Ford Formation

Eagle Ford deposits are mostly shale to mudstone, siltstone, and flaggy limestone commonly between 15 and 30 ft thick. The lower part of the unit is siltstone, some very fine grained sandstone, and flaggy limestone. This lower part is overlain by dark-gray shale to mudstone and flaggy limestone. Eagle Ford strata weather easily and form flat to gently rolling topography. Outcrops are rare.

Austin Group

The Austin Group, also called the Austin Chalk, consists of thin- to thick-bedded chalk, limestone, and argillaceous limestone. The chalk is mostly microgranular calcite, along with some foraminiferal tests. The unit is 135 to 200 ft thick and is commonly associated with thick black soil and relatively low relief areas.

Northeast of the study area in the Austin area, Young (1985) identified seven Austin Group units (in ascending order): the Atco, Vinson, Jonah, Dessau, Burditt, Pflugerville, and McKown. In Bexar, Comal, and Hays Counties of the study area, Young (1985) determined that only the Atco, Vinson, and Dessau exist. The other Austin units apparently pinch out toward the study area and the San Marcos Platform.

Basalt

Minor occurrences of basalt exist in the study area, and these are thought to be related to Late Cretaceous volcanism that is evident in Central Texas areas outside the study area (Lonsdale, 1927; Baldwin and Adams, 1971; Brown and others, 1974; Young and others, 1981; Ewing and Caran, 1982). The most accessible basalt occurrence in the map area is a northwest-striking dike cutting Glen Rose limestone in the Honey Creek State Natural Area adjacent to Guadalupe River State Park in northwest Comal County. S. C. Caran (personal communication, 1990) traced small outcrops of basalt and basalt float across approximately 0.5 mi, although the dike is most visible in a small outcrop at Honey Creek. Cooper (1964) also mapped basalt float in an area that is located approximately 3 mi southeast and along strike of the Honey Creek dike.

Lower Taylor Group

Lower Taylor Group deposits, as much as 400 ft thick, comprise marl, argillaceous limestone, limestone, and some clay–claystone to mud–mudstone. Some of the limestone has a chalky texture. The unit weathers to thick black soil and generally covers low-relief areas. Outcrops are rare. Lower Taylor soils are more calcareous than soils of the upper Taylor Group, and previous soil surveys (Taylor and others, 1966; Ramsey and Bade, 1977) were useful in interpreting the contact between these two units.

For this study, lower Taylor Pecan Gap and Anacacho Formations have not been divided or separately identified. Pecan Gap deposits become thinner toward the west across the study area, and they probably interfinger with Anacacho strata, which thin across the study area toward the east (Brown and others, 1974; Young, 1985). Ewing (1996) briefly discussed some stratigraphic relationships of the Austin, Pecan Gap, and Anacacho units in Bexar County, and he proposed the name "Wetmore marl" for the marl-to-argillaceous limestone interval between the Austin Group and upper Taylor Groups.

Upper Taylor Group and Navarro Group

Cretaceous upper Taylor and Navarro strata and overlying Paleocene to Eocene Midway deposits are undivided on the geologic map because these units have similar lithologies and soils, making them extremely difficult to differentiate. These units compose only a relatively small part of the study area. They weather to thick, black, clayey soil across an area of relatively low topographic relief. Outcrops generally do not exist. The upper Taylor consists mostly of clay–claystone to mud–mudstone, and the Navarro, composed of marl and clay–claystone to mud–mudstone, contains some thin siltstone and sandstone beds. Combined, these two units are about 950 ft thick.

Tertiary

Tertiary deposits (fig. 4) are present only in a small southeast part of the study area (map). The Paleocene Midway Group was deposited in a marine-slope environment (Galloway and others, 1991). Overlying the Midway Group are the Paleocene–Eocene Wilcox Group sediments, which represent one of the major Cenozoic progradational episodes in the Gulf of Mexico. Much younger Pliocene- to Pleistocene-age fluvial gravel and sand deposits typically cap topographically high areas in the south-southeast part of the study area (map).

Midway Group

Midway Group clay–claystone to mud–mudstone, siltstone, and sandstone are between 100 and 400 ft thick. They weather to thick, black, clayey soil over an area of relatively low topographic relief. Outcrops generally do not exist, and Midway deposits are undivided from underlying Cretaceous upper Taylor and Navarro sediments on the geologic map of the study area (map). The lower part of the Midway is glauconitic, and phosphatic nodules and pebbles have been reported to exist at the base of the unit (Sellards and others, 1932; Brown and others, 1974).

Wilcox Group

Wilcox Group strata in the study area are mudstone and sandstone. Outcrops are rare, and the interpreted contact with the underlying Midway Group is based on recognition of the sandier soils that are associated with the Wilcox Group. Regionally the Wilcox is composed of fluvial, deltaic, and shore-zone sequences (Galloway and others, 1991).

Quaternary–Upper Tertiary

Gravel and sand deposits locally cap topographically high areas in the south part of the map area. The gravel is mostly well rounded pebble- to cobble-sized chert and limestone, although quartz and metamorphic rock also exist at some locations. These deposits are commonly cemented by caliche. Thicknesses range from several feet to more than 10 ft. The deposits are possibly equivalent to the upper Tertiary–Quaternary Uvalde Gravel, which covers older Tertiary and Cretaceous deposits west of the study area (Brown and others, 1974).

Quaternary

Quaternary alluvial deposits include the Pleistocene Leona Formation, probable Holocene terrace alluvium and stream-bed alluvium, and undivided slope-wash and terrace alluvium. These deposits are mostly made up of silt, sand, gravel, and some clay. The Leona Formation, possibly as thick as 60 ft in some locations, may represent older Quaternary fluvial deposits. Younger stream terraces are inset against the Leona Formation and older Tertiary and Cretaceous strata. Terrace deposits along the larger streams, such as the Blanco and Guadalupe Rivers, may be as thick as 20 ft. Stream-bed alluvium is generally very thin, and areas mapped as stream-bed alluvium commonly include local bedrock outcrops (map).

Impact of Geology on Urban and Rural Population Growth and Land Use

Urban growth and population increases in nearby rural areas have created demands on land and water resources and cause increases in construction activities. In the study area, geological considerations are key to managing and planning the use of land and water resources and conducting responsible, cost-effective construction practices at economic costs (Flawn, 1965; Woodruff, 1979).

Geology and Construction

The construction of foundations, ease of excavating rock, evaluation of slope stabilities and drainages, siting of landfills and other waste-disposal facilities, and construction and development in areas of perennial water seeps or potential ground-water recharge are typical aspects of construction, land use, and urban planning in the study area that benefit from basic geological information. Foundation designs vary according to the ability of the soil or rock to support the foundation and structure (buildings, bridges, roads, etc.). Thick, swelling-clay soils may require foundation designs different from what limestone with thinner soils might. For example, swelling and shrinking clay of the Del Rio Formation is notorious for causing structural problems. Thick, clay-rich deposits of the Upper Taylor Group also have the potential to cause problems if foundations are not properly designed. Complexly faulted areas may have juxtaposed strata and associated soils with varying physical properties, creating potential construction/foundation problems.

Occurrence of solution cavities is another possible concern of engineers designing foundations. Solution features such as sinkholes and caves commonly serve as key ground-water recharge conduits for the aquifers. Only the sinkholes that are most noticeable on aerial photographs are illustrated on this report's geologic map. Mapping of solution features at a more detailed scale than that of the map is required for responsible development throughout much of the study area. Solution cavities of various dimensions occur within the Kainer and Person Formations, an areally extensive karstic outcrop belt of limestone and dolomitic limestone of the Edwards Group. Caves, sinkholes, solution-widened fractures and bedding planes, and other karst features also commonly occur within other Cretaceous units, such as the Glen Rose, Walnut, and Georgetown Formations.

The ease of excavating rock for construction projects impacts construction planning and costs. The more competent units of the Glen Rose, Walnut, Kainer, Person, Georgetown, and Buda Formations are relatively more difficult to excavate than are the more clay-rich and thinly bedded strata of the Del Rio, Eagle Ford, Austin, and Taylor Formations. Different techniques of excavating may be required for different units. Chert is very common in parts of the Kainer and Person Formations, and its occurrence and hardness can cause difficulties for some excavation methods.

Landslides or slumps may form by slope failure in clay-rich units, in limestone above the thicker clay-rich strata, in interbedded limestone and marl units, and along drainageways in sandy and gravelly alluvium. Many slumps are caused by natural oversteepening of slopes due to erosion and by human-induced removal of slope toes (base of slopes) during construction. Water saturation may also contribute to slope failures. Slumps are common where Del Rio clay–claystone to mud–mudstone occurs along steeper slopes, bluffs, and construction cuts into the unit. Layers of Buda limestone, which commonly caps hillsides of Del Rio, are also susceptible to slope failure. Where the Glen Rose, Walnut, Kainer, Person, Georgetown, and Austin units are composed of limestones interbedded with softer, argillaceous limestone and marl beds, oversteepening of natural bluffs and excavations may also cause landslides. Slumping along oversteepened slopes of drainageways can also occur in clay-rich Taylor deposits and sandy and gravelly alluvium, sometimes near bridges and roads.

Drainageways in the study area are subject to flooding by local rainstorms. Caran and Baker (1986) reported that high-magnitude floods occur with greater frequency in the Balcones Escarpment area than in any other region of the United States. Although the comparison of flood frequency and magnitude between that of the entire nation and that of the Balcones Escarpment can be scientifically debated, drainageways within the Balcones Escarpment area are certainly susceptible to relatively frequent floods. Urbanization, which results in increased impervious cover and, hence, increases in runoff, may also elevate flooding potential in some localities. Properly engineered flood-prevention construction, however, may protect (or at least partly protect) some lower elevation areas from flooding.

Lower terraces and areas of young alluvium illustrated on the geologic map indicate the location of some potentially flood-prone areas.

Water seeps can be common, especially during periods of frequent rainfall. Seeps are generally seasonal. They commonly occur along bedding planes, where more permeable strata overlie relatively impermeable strata, or along fractures. Seeps can occur within any of the strata, although most commonly within the interbedded limestone and argillaceous limestone of the Glen Rose, Kainer, and Person Formations. They also typically occur at the Walnut–Kainer, Del Rio–Buda, and alluvium–underlying-strata contacts.

Geology is an aspect crucial to the siting of landfills and other waste-disposal sites. Siting such facilities requires integrating certain site-specific geology, engineering, and urban planning, which are beyond the scope of this report. However, some general geological considerations include (1) physical properties of the units, such as the ability of the unit to absorb and disperse fluids; (2) flood-prone areas, which should be avoided; and (3) localities of various local water supplies to ensure prevention of potential contamination. For example, a potential landfill site located within the Taylor Group could benefit from the unit's clay-rich composition, which would help prevent leachate from being transmitted to a water supply.

Geology and Land Use

The mapped region includes ranch, farm, urban, and undeveloped areas. Rural land is gradually being transformed into urban suburbs and smaller ranches and farms that are owned by urban workers. Historically much of the clay-rich and sandy land has been used for farming, whereas the more rocky limestone areas have been used as rangeland. Construction materials such as rock aggregate, cement, and sand and gravel are generally in demand as a result of construction related to population growth and urbanization. Large limestone quarries are located along the Balcones Escarpment in the Kainer, Person, and Austin units. These quarries lie near major roads, railroad lines, and urbanized areas. Smaller limestone pits that occur throughout the rural areas are used mostly for road construction and maintenance. Sand- and gravel-mining operations are mostly south and southeast of the Balcones Escarpment. Numerous active and inactive sand and gravel pits occur along terraces of the larger rivers and creeks.

Demands on the land for recreation have also increased as population has increased. Two large reservoirs, Canyon and Medina Lakes, are used for recreation, as well as serving as the regional water supply. Parts of the Guadalupe River are also seasonal recreation areas. Maintaining good water quality for these bodies of water through well-managed urbanization and development is not only economically important but it also contributes to the local quality of life. Geology-related considerations can aid in good management practices. For example, in porous limestone areas, septic-tank installations (particularly high-density installations) require proper engineering to work efficiently so that they are not potential sources of local pollution. In construction areas, appropriate precautions can be taken to prevent or greatly reduce the amount of sediment carried by surface runoff into creeks, rivers, and lakes. Recognition and preservation of key recharge features such as large sinkholes and caves can aid in preserving water quality.

Other recreation areas influenced by local geology include two state parks and privately operated tourist caves. Caves are numerous in the limestone and dolomitic limestone of the Kainer, Person, and Glen Rose Formations (National Speleological Society, 1964; Kastning, 1986; Veni, 1988; Vauter, 1992; Elliott and Veni, 1994). Several caves have been developed for public touring, although most are not accessible to the general public. Guadalupe River State Park and adjacent Honey Creek Natural Area lie in western Comal County along a scenic part of the Guadalupe River where the river has incised Glen Rose, Hensell, and Cow Creek limestones, creating steep bluffs along the river. Guadalupe River State Park also contains a basalt dike that has cut through the older limestone strata. Government Canyon State Natural Area in western Bexar County captures the unique physiographic and vegetative variations that occur along the Balcones Escarpment. At the Government Canyon area, the 140-ft-high escarpment is a fault-line scarp of a fault having more than 500 ft of displacement. The escarpment divides the park into two distinct areas. One area consists of rugged limestone hills (Glen Rose through Kainer Formations) dissected by steep canyons and gullies. The area of the park on the downthrown side of the fault is flat to gently rolling topography developed on softer limestone and marl (Austin Formation) with clay-rich soils and gravelly and locally caliche-capped terrace alluvium.

Geology and Water Resources

The most important natural resource of the study area is ground water. The Edwards aquifer, currently designated as the sole source of water in San Antonio, is also the main water supply for a large rural area south of the Balcones Escarpment. In the north-central and northwest part of the study area, the Trinity aquifer is also an important source of ground water. A local and smaller source of ground water for some domestic and livestock use is sandy and gravelly alluvial deposits south and southeast of the Balcones Escarpment. Surface water of numerous small reservoirs and two larger reservoirs, Canyon and Medina Lakes, is also important.

Edwards Aquifer

In the study area, the designation "Edwards aquifer" (Klempt and others, 1979; Maclay and Small, 1986) commonly refers to the San Antonio segment of the aquifer along and south of the Balcones Fault Zone (fig. 1). In the northwest part of the map area, Edwards Group strata that cap hills and the east margin of the Edwards Plateau also contain some water but are not considered part of the San Antonio segment of the aquifer.

The San Antonio segment of the aquifer that is within the map area is composed of Georgetown, Person, Kainer, and Walnut strata. Its combined thickness is between 500 and 650 ft. Georgetown and Walnut limestones are considered minor parts of the aquifer because their combined thickness is generally less than 100 ft of relatively lower porosity strata. Previous workers subdivided the strata that make up the aquifer into eight informal aquifer subdivisions (listed earlier in this report) because different stratal intervals have somewhat different physical characteristics (Maclay and Small, 1986). Del Rio clay–claystone to mud–mudstone overlies the aquifer strata, and beneath the Edwards aquifer lie limestone and marl of the Glen Rose Formation. Because the upper part of the Glen Rose Formation has permeabilities generally lower than those of the Kainer and Person Formations, 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 Kainer and Person Formations' outcrop belt approximately defines the main recharge area and unconfined part of the aquifer. The subsurface aquifer strata south and southeast of the Kainer and Person outcrop belt represent the confined aquifer. 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, 1998), with well-developed fracture and karstic conduit systems that allow rapid movement of water.

The structural position of the San Antonio segment of the Edwards aquifer is controlled by normal faults and associated gentle folds (Collins, 1995k; Collins and Hovorka, 1997). 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 Comal County in the east part of the map area, the confined aquifer is mostly less than 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 approximately 1,000 ft. Collins and Hovorka (1997) determined that several faults in the map area exceed or nearly exceed the thickness of the aquifer strata; thus, they are potential barriers or partial barriers to ground-water flow. The San Antonio relay ramp, discussed earlier in the structure section of this report, represents an area where continuity from the recharge zone to the subsurface confined aquifer is relatively good because permeable strata are more continuous within the ramp or gentle monocline than across larger faults.

Trinity Aquifer

The Trinity aquifer system of Central and South-Central Texas (Reeves, 1967; Ashworth, 1983, 1997; Barker and Ardis, 1996; Mace and others, 2000) consists of the water-bearing units of the Trinity Group, which include the Cow Creek, Hensell, and Glen Rose Formations in the mapped area. This aquifer provides water to municipal, domestic, irrigation, and livestock wells. Parts of the lower Glen Rose Formation yield small to moderate amounts of fresh to slightly saline water, and the upper Glen Rose yields typically smaller quantities of poorer quality, slightly saline water (Reeves, 1967; Ashworth, 1983, 1997; Waterreus, 1992). Wells in the Hensell Formation yield generally smaller quantities of water in the study area than do wells in the lower Glen Rose. Some Hensell ground water contains high levels of sulfate and chloride and, locally, iron. Toward the north and northwest of the study area, Hensell strata may have increased yields of water, possibly owing to the facies change from marine sandy limestone, dolomite, and sandstone to continental deposits of silt, sand, and conglomerate. Cow Creek limestone generally yields small to moderate amounts of fresh to saline water.

Acknowledgments

Research for the map and report was supported by the U.S. Geological Survey, COGEOMAP Program, and National Cooperative Geologic Mapping Program, under U.S. Geological Survey award numbers 14-08-001-A0812, 14-08-0001-A0885, 1434-93-A-1174, 1434-94-A-1255, 1434-95-A-1381, and 1434-HQ-96-AG-01519. The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Jay A. Raney served as Principal Investigator for the project, mapped part of the northwest study area during 1991, and reviewed the map and report. Robert W. Baumgardner also mapped part of the northwest study area during 1991. Map digitization was done by Sarah Dale and John Andrews under the direction of Tom Tremblay. Map graphics were prepared by William Bergquist, and text figures were done by Nancy Cottington under the supervision of Joel L. Lardon, Graphics Manager. The map and text benefited from the helpful comments of reviewers T. F. Hentz, S. D. Hovorka, R. C. Smyth, and S. C. Ruppel. Others contributing to the production of this report were Susan Lloyd, word processing and design, and Lana Dieterich, editing, both under the supervision of Susann Doenges, Chief Editor.

References

Abbott, P. L., 1966, The Glen Rose section in the Canyon Reservoir area, Comal County, Texas: University of Texas, Austin, Master's thesis, 146 p.

__________ 1973, The Edwards Limestone in the Balcones Fault Zone, South-Central Texas: The University of Texas at Austin, Ph.D. dissertation, 122 p.

Abbott, P. L., and Woodruff, C. M., Jr., eds., 1986, The Balcones Escarpment—geology, hydrology, ecology and social development in Central Texas: The University of Texas at Austin, Bureau of Economic Geology, published for Geological Society of America Annual Meeting, San Antonio, Texas, November, 200 p.

Amsbury, D. L., 1974, Stratigraphic petrology of lower and middle Trinity rocks on the San Marcos platform, South-Central Texas: Louisiana State University, Geoscience and Man, v. 8, p. 1–35.

Arnow, Ted, 1959, Ground-water geology of Bexar County, Texas: Texas Board of Water Engineers Bulletin 5911, 36 p.

Ashworth, J. B., 1983, Ground-water availability of the Lower Cretaceous formations in the Hill Country of South-Central Texas: Texas Department of Water Resources Report 273, 172 p.

__________ 1997, Trinity aquifer system of the Texas Hill Country, *in* Woodruff, C. M., Jr., ed., Environment and land restoration in the central Texas Hill Country: a geologic excursion to Selah, Bamberger Ranch, Blanco County, Texas: Austin Geological Society, Guidebook 17, p. 49–58.

Baldwin, O. C., and Adams, J. A. S., 1971, K^{40}/Ar^{40} ages of the alkalic igneous rocks of the Balcones fault trend of Texas: Texas Journal of Science, v. 22, p. 223–231.

Barker, R. A., and Ardis, A. F., 1996, Hydrologic framework of the Edwards-Trinity aquifer system, west-central Texas: U.S. Geological Survey Professional Paper 1421-B, 61 p. + pls.

Barnes, V. E., 1992, Geologic map of Texas: The University of Texas at Austin, Bureau of Economic Geology, scale 1:500,000, 4 sheets.

Baumgardner, R. W., Jr., and Collins, E. W., 1991, Geologic map of the Hunter 7.5-minute quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

Bills, T. V., Jr., 1957, Geology of Waco Springs quadrangle, Comal County, Texas: University of Texas, Austin, Master's thesis, 106 p.

Brown, T. E., Waechter, N. B., and Barnes, V. E., 1974, San Antonio sheet: The University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000, revised 1983.

Caran, S. C., and Baker, V. R., 1986, Flooding along the Balcones Escarpment, Central Texas, *in* Abbott, P. L., and Woodruff, C. M., eds., The Balcones Escarpment—geology, hydrology, ecology and social development in Central Texas: The University of Texas at Austin, Bureau of Economic Geology, published for Geological Society of America Annual Meeting, San Antonio, Texas, November, p. 1–14.

Caran, S. C., Woodruff, C. M., Jr., and Thompson, E. J., 1981, Lineament analysis and inference of geologic structure—examples from the Balcones/Ouachita trend of Texas: Gulf Coast Association of Geological Societies Transactions, v. 31, p. 59–69.

Collins, E. W., 1992a, Geologic map of the Anhalt quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1992b, Geologic map of the Fischer quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1992c, Geologic map of the Smithson Valley quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1992d, Geologic map of the Spring Branch quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1993a, Fracture zones between overlapping en echelon fault strands: outcrop analogs within the Balcones Fault Zone, Central Texas: Gulf Coast Association of Geological Societies Transactions, v. 43, p. 77–85.

__________ 1993b, Geologic map of the Bat Cave quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1993c, Geologic map of the Bulverde quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1993d, Geologic map of the Marion quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1993e, Geologic map of the McQueeney quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1993f, Geologic map of the New Braunfels East quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1993g, Geologic map of the New Braunfels West quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1993h, Geologic map of the Schertz quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1994a, Geologic map of the Bergheim quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1994b, Geologic map of the Camp Bullis quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1994c, Geologic map of the Castle Hills quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1994d, Geologic map of the Kendalia quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1994e, Geologic map of the Longhorn quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1994f, Geology of the Balcones Fault Zone along the growth corridor of San Antonio, Boerne, Wimberley, and New Braunfels, South-Central Texas (ext. abs.): Gulf Coast Association of Geological Societies Transactions, v. 44, p. 125–126.

__________ 1995a, Geologic map of the Comfort quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1995b, Geologic map of the Helotes quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1995c, Geologic map of the Jack Mountain quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1995d, Geologic map of the Medina Lake quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1995e, Geologic map of the Pipe Creek quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1995f, Geologic map of the Ranger Creek quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1995g, Geologic map of the San Geronimo quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1995h, Geologic map of the Turkey Knob quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1995i, Geologic map of the Van Raub quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1995j, Geologic map of the Waring quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1995k, Structural framework of the Edwards aquifer, Balcones Fault Zone, Central Texas: Gulf Coast Association of Geological Societies Transactions, v. 45, p. 135–142.

Collins, E. W., Baumgardner, R. W., Jr., and Raney, J. A., 1991a, Geologic map of the Sattler quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

__________ 1991b, Geologic map of the Wimberley quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

Collins, E. W., and Hovorka, S. D., 1997, 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: The University of Texas at Austin, Bureau of Economic Geology Miscellaneous Map No. 38, 14-p. text, 1 sheet, scale 1:250,000.

Cooper, J. D., 1964, Geology of Spring Branch area, Comal and Kendall Counties, Texas: University of Texas, Austin, Master's thesis, 183 p.

DeCook, K. J., 1963, Geology and ground-water resources of Hays County, Texas: U.S. Geological Survey Water-Supply Paper 1612, 72 p.

Elliott, W. R., and Veni, George, eds., 1994, The caves and karst of Texas: a guidebook for the 1994 Convention of the National Speleological Society, with emphasis on the southwestern Edwards Plateau, 342 p.

Ewing, T. E., 1991a, Structural framework, *in* Salvador, Amos, ed., The Gulf of Mexico Basin: Geological Society of America, The Geology of North America, v. J, p. 31–52.

__________ 1991b, The tectonic framework of Texas—text accompanying "The Tectonic Map of Texas": The University of Texas at Austin, Bureau of Economic Geology, 36 p.

__________ 1996, Rocks, landscapes, and man: urban geology of the San Antonio area: South Texas Geological Society Field Trip Guidebook, 133 p.

Ewing, T. E., and Caran, S. C., 1982, Late Cretaceous volcanism in South and Central Texas—stratigraphic, structural and seismic models: Gulf Coast Association of Geological Societies Transactions, v. 32, p. 137–145.

Fisher, W. L., and Rodda, P. U., 1969, Edwards Formation (Lower Cretaceous) of Texas: dolomitization of a carbonate platform system: American Association of Petroleum Geologists Bulletin, v. 53, no. 1, p. 55–72.

Flawn, P. T., 1965, Geology and urban development: Baylor Geologic Studies, v. 8, p. 5–7.

Flawn, P. T., Goldstein, A., Jr., King, P. B., and Weaver, C. E., 1961, The Ouachita System: University of Texas, Austin, Bureau of Economic Geology Publication 6120, 401 p.

Galloway, W. E., Bebout, D. G., Fisher, W. L., Dunlap, J. B., Jr., Cabrera-Castro, R., Lugo-Rivera, J. E., and Scott, T. M., 1991, Cenozoic, *in* Salvador, Amos, ed., The Gulf of Mexico Basin: Geological Society of America, The Geology of North America, v. J, p. 245–324.

Garner, L. E., and Young, K. P., 1976, Environmental geology of the Austin area: an aid to urban planning: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 86, 39 p.

George, W. O., 1952, Geology and ground-water resources of Comal County, Texas: U.S. Geological Survey Water-Supply Paper 1138, 126 p.

Gustavson, T. C., and Wermund, E. G., project directors, 1985, The Guadalupe–Lavaca–San Antonio–Nueces river basins regional study, San Antonio East–Llano East sheets: The University of Texas at Austin, Bureau of Economic Geology, scale 1:250,000, 5 pls.

Grimshaw, T. W., 1970, Geology of Wimberley area, Hays and Comal Counties, Texas: The University of Texas at Austin, Master's thesis, 104 p.

__________ 1976, Environmental geology of urban and urbanizing areas: a case study from the San Marcos area, Texas: The University of Texas at Austin, Ph.D. dissertation, 244 p.

Hanson, J. A., and Small, T. A., 1995, Geologic framework and hydrogeologic characteristics of the Edwards aquifer outcrop, Hays County, Texas: U.S. Geological Survey Water-Resources Investigations Report 95-4265, 10 p.

Holt, C. L. R., Jr., 1959, Geology and ground-water resources of Medina County, Texas: U.S. Geological Survey, U.S. Geological Survey Water-Supply Paper 1422, 213 p.

Hovorka, S. D., 1996, High-frequency cyclicity during eustatic sea-level rise: Edwards Group of the Balcones Fault Zone: Gulf Coast Association of Geological Societies Transactions, v. 46, p. 179–184.

Hovorka, S. D., Mace, R. E., and Collins, E. W., 1998, Permeability structure of the Edwards aquifer, South Texas—implications for aquifer management: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 250, 55 p.

Hovorka, S. D., Dutton, A. R., Ruppel, S. C., and Yeh, J. S., 1996, Edwards aquifer ground-water resources: geologic controls on porosity development in platform carbonates, South Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 238, 75 p.

Jones, J. O., Bonem, R. M., Hawthorne, J. M., Farlow, J. O., Pate, K. A., and Eifert, T. L., 1998, Dinosaur tracks from a 100-year flood event, Kendall County, Texas (abs.): Geological Society of America, South-Central Section, Abstracts with Programs, v. 30, no. 3, p. 9.

Kastning, E. H., 1986, Cavern development in the New Braunfels area, Central Texas, *in* Abbott, P. L., and Woodruff, C. M., eds., The Balcones Escarpment—geology, hydrology, ecology and social development in Central Texas: The University of Texas at Austin, Bureau of Economic Geology, published for Geological Society of America Annual Meeting, San Antonio, Texas, November, p. 91–100.

King, V. L., Jr., 1957, Geology of the Mission Valley quadrangle, Comal County, Texas: University of Texas, Austin, Master's thesis, 85 p.

Klempt, W. B., Knowles, T. R., Elder, G., and Sieh, T., 1979, Ground-water resources and model applications for the Edwards (Balcones Fault Zone) aquifer in the San Antonio region, Texas: Texas Department of Water Resources Report 239, 88 p.

Larsen, P. H., 1988, Relay structures in a Lower Permian basement-involved extension system, East Greenland: Journal of Structural Geology, v. 10, no. 1, p. 3–8.

Liddle, R. A., 1918, The geology and mineral resources of Medina County: University of Texas, Austin, Bureau of Economic Geology, Bulletin No. 1860, 177 p.

Lonsdale, J. T., 1927, Igneous rocks of the Balcones fault region of Texas: University of Texas, Austin, Bureau of Economic Geology, Bulletin No. 2744, 178 p.

Mace, R. E., Chowdury, A. H., Anaya, R., and Way, S. C., 2000, A numerical groundwater flow model of the upper and middle Trinity aquifer, Hill Country area: Texas Water Development Board Open File Report 00-02, 62 p.

Maclay, R. W., and Small, T. A., 1986, Carbonate geology and hydrology of the Edwards aquifer in the San Antonio area, Texas: Texas Water Development Board Report 296, 90 p.

Marsh, W. M., and Marsh, N. L., 1994, Microtopography, runoff processes, sediment transport, and their implications for land use planning in the Central Texas Hill Country: Gulf Coast Association of Geological Societies Transactions, v. 44, p. 447–456.

Martin, K. G., 1967, Stratigraphy of the Buda Limestone, South-Central Texas, *in* Hendricks, Leo, ed., Comanchean (Lower Cretaceous) stratigraphy and paleontology of Texas: Society of Economic Paleontologists and Mineralogists, Permian Basin Section, Publication No. 67-8, p. 287–299.

McFarlan, Edward, Jr., and Menes, L. S., 1991, Lower Cretaceous, *in* Salvador, Amos, ed., The Gulf of Mexico Basin: Geological Society of America, The Geology of North America, v. J, p. 181–204.

Moore, C. H., Jr., 1964, Stratigraphy of the Fredericksburg Division, South-Central Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 52, 48 p.

__________ 1996, Anatomy of a sequence boundary—Lower Cretaceous Glen Rose/Fredericksburg, Central Texas Platform: Gulf Coast Association of Geological Societies Transactions, v. 46, p. 313–320.

Moore, C. H., Jr., and Bebout, D. G., 1989, Carbonate rock sequences from the Cretaceous of Texas—San Antonio to Austin, Texas: 28th International Geological Congress, Field Trip Guidebook T376, 47 p.

Murray, G. E., 1961, Geology of the Atlantic and Gulf coastal province of North America: New York, Harper Brothers, 692 p.

National Speleological Society and Reddell, J. R., eds., 1964, A guide to the caves of Texas and 1964 N.S.S. Convention field trips: National Speleological Society, Guidebook 5, 61 p.

Newcomb, J. H., 1971, Geology of Bat Cave quadrangle, Comal and Bexar Counties, Texas: The University of Texas at Austin, Master's thesis, 104 p.

Noyes, A. P., Jr., 1957, Geology of Purgatory Creek area, Hays and Comal Counties, Texas: University of Texas, Austin, Master's thesis, 94 p.

Peacock, D. C. P., and Sanderson, D. J., 1991, Displacements, segment linkage, and relay ramps in normal fault zones: Journal of Structural Geology, v. 13, no. 6, p. 721–733.

__________ 1994, Geometry and development of relay ramps in normal fault systems: American Association of Petroleum Geologists Bulletin, v. 78, no. 2, p. 147–165.

Perkins, B. F., 1974, Paleoecology of a rudist reef complex in the Comanche Cretaceous Glen Rose Limestone of Central Texas: Louisiana State University, Geoscience and Man, v. 8, p. 131–175.

Pittman, J. G., 1989, Stratigraphy of the Glen Rose Formation, western Gulf coastal plain: Gulf Coast Association of Geological Societies Transactions, v. 39, p. 247–264.

Ramsey, R. N., and Bade, N. P., 1977, Soil survey of Guadalupe County, Texas: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with Texas Agricultural Experiment Station, 80 p.

Raney, J. A., and Collins, E. W., 1991, Geologic map of the Devil's Backbone 7.5-minute quadrangle, Texas: The University of Texas at Austin, Bureau of Economic Geology Open-File Map, scale 1:24,000.

Reeves, R. D., 1967, Ground-water resources of Kendall County, Texas: Texas Water Development Board, Report 60, 100 p.

Reeves, R. D., and Lee, F. C., 1962, Ground-water geology of Bandera County, Texas: Texas Water Commission Bulletin 6210, 78 p.

Rodda, P. U., Fisher, W. L., Payne, W. R., and Schofield, D. A., 1966, Limestone and dolomite resources, Lower Cretaceous rocks, Texas: University of Texas, Austin, Bureau of Economic Geology Report of Investigations No. 56, 286 p.

Rose, P. R., 1972, Edwards Group, surface and subsurface, Central Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 74, 198 p.

__________ 1974, Edwards Group and equivalents, eastern Edwards Plateau, Texas: field trip overview, *in* Rose, P. R., ed., Stratigraphy of the Edwards Group and equivalents, eastern Edwards Plateau, Texas: Guidebook for American Association of Petroleum Geologists–Society of Economic Paleontologists and Mineralogists Field Trip: South Texas Geological Society, p. 1–12.

Roy, E. C., Jr., 1986, A summary of the Mesozoic geology of south-central Texas: Compass of Sigma Gamma Epsilon, v. 63, no. 4, p. 145–153.

Sellards, E. H., 1919, The geology and mineral resources of Bexar County: University of Texas, Austin, Bureau of Economic Geology, Bulletin No. 1932, 202 p.

Sellards, E. H., Adkins, W. S., and Plummer, F. B., 1932, The geology of Texas, v. I, stratigraphy: University of Texas, Austin, Bureau of Economic Geology, Bulletin No. 3232, 1007 p.

Sellards, E. H., Baker, C. L., and others, 1934, The geology of Texas, v. II, structural and economic geology: University of Texas, Austin, Bureau of Economic Geology, Bulletin No. 3401, 884 p.

Shaw, S. L., 1974, Geology and land-use capability of the Castle Hills quadrangle, Bexar County, Texas: The University of Texas at Austin, Master's thesis, 131 p.

Small, T. A., and Hanson, J. A., 1994, Geologic framework and hydrogeologic characteristics of the Edwards aquifer outcrop, Comal County, Texas: U.S. Geological Survey Water-Resources Investigations 94-4117, 10 p., 1 pl., scale 1:75,000.

Smith, C. I., 1964, Physical stratigraphy and facies analysis, Lower Cretaceous limestones, Edwards Plateau, West Texas: Houston, Texas, Shell Development Company, EPR Special Report 45, 138 p.

Sohl, N. F., Martinez, Eduardo, Salmeron-Urena, Pedro, and Soto-Jaramillo, Fidel, 1991, Upper Cretaceous, *in* Salvador, Amos, ed., The Gulf of Mexico Basin: Geological Society of America, The Geology of North America, v. J, p. 205–244.

Stein, W. G., 1993, Hydrogeologic map and characteristics of the recharge zone of the Edwards aquifer, Bexar County, Texas: The University of Texas at San Antonio, Master's thesis, 84 p.

Stein, W. G., and Ozuna, G. B., 1995, Geologic framework and hydrogeologic characteristics of the Edwards aquifer recharge zone, Bexar County, Texas: U.S. Geological Survey Water-Resources Investigations 95-4030, 8 p., 1 map, scale 1:75,000.

Stricklin, F. L., and Amsbury, D. L., 1974, Depositional environments on a low-relief carbonate shelf, middle Glen Rose Limestone, Central Texas: Louisiana State University, Geoscience and Man, v. 8, p. 53–67.

Stricklin, F. L., Jr., Smith, C. I., and Lozo, F. E., 1971, Stratigraphy of Lower Cretaceous Trinity deposits of Central Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 71, 63 p.

Taylor, F. B., Hailey, R. B., and Richmond, D. L., 1966, Soil survey of Bexar County, Texas: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with Texas Agricultural Experiment Station, 126 p.

Tremblay, T. A., Dale, Sarah, and Andrews, John, 1997, GIS data base of the Geologic map of the New Braunfels 30 × 60 Minute Quadrangle: The University of Texas at Austin, Bureau of Economic Geology, Open-File GIS Data Base.

U.S. Geological Survey, 1937, Geologic map of Texas: Miscellaneous Map, scale 1:500,000.

Vauter, B. K., 1992, Geological influences on cavern formation near Natural Bridge Caverns, Texas: Baylor University, Bachelor's thesis, 71 p.

Veni, George, 1988, The caves of Bexar County, 2d ed.: Austin, Texas, Texas Memorial Museum Speleological Monograph 2, 300 p.

Waddell, R. K., Jr., 1977, Environmental geology of the Helotes quadrangle, Bexar County, Texas: The University of Texas at Austin, Master's thesis, 161 p.

Waterreus, P. A., 1992, Hydrogeology of the Camp Bullis area, northern Bexar County, Texas: The University of Texas at San Antonio, Master's thesis, 186 p.

Weeks, A. W., 1945, Balcones, Luling, and Mexia fault zones in Texas: American Association of Petroleum Geologists Bulletin, v. 29, no. 12, p. 1733–1737.

Whitney, F. L., 1957, Geologic maps of Bracken, Hunter, New Braunfels, and Smithson Valley quadrangles, *in* Young, K. P., University of Texas, Austin, Bureau of Economic Geology Miscellaneous Map No. 16, scale: 1 inch = 1 mi.

Wilding, L. P., 1997, A reappraisal of the Brackett soil series, *in* Woodruff, C. M., Jr., ed., Environment and land restoration in the Central Texas Hill Country: Austin Geological Society, Guidebook 17, p. 59–68.

Woodruff, C. M., Jr., 1979, Land resource overview of the capital area planning council region, Texas—a nontechnical guide: The University of Texas at Austin, Bureau of Economic Geology, 29 p., 4 pl.

Woodruff, C. M., Jr., Wilding, L. P., and Marsh, W. M., 1994, Bedrock, soils, and microtopography of a test area within the Barton Creek watershed, western Travis County, Texas, *in* Johns, D. A., and Woodruff, C. M., Jr., eds., Edwards aquifer—water quality and land development in the Austin area, Texas: field trip guidebook, Gulf Coast Association of Geological Societies 44th Annual Convention, Austin, Texas, p. 37–41.

Woodruff, C. M., Jr., Rose, P. R., and Abbott, P. L., 1998, The name game—parsimony and public communication: GSA Today, v. 8, no. 8, p. 24.

Young, Keith, 1967, Comanche Series (Cretaceous), South-Central Texas, *in* Hendricks, Leo, ed., Comanchean (Lower Cretaceous) stratigraphy and paleontology of Texas: Society of Economic Paleontologists and Mineralogists, Permian Basin Section, Publication No. 67-8, p. 9–29.

__________ 1985, The Austin Division of Central Texas, *in* Young, Keith, and Woodruff, C. M., eds., Austin Chalk in its type area—stratigraphy and structure: Austin Geological Society, Guidebook 7, p. 3–52.

Young, K. P., Caran, S. C., and Ewing, T. E., 1981, Cretaceous volcanism in the Austin area, Texas: Austin Geological Society, Field Trip Guidebook 4, 43 p.

Young, Keith, and Woodruff, C. M., 1985, Austin Chalk in its type area—stratigraphy and structure: Austin Geological Society, Guidebook 7, 88 p.