# Chapter 2

# Geology of the Gulf Coast Aquifer, Texas

Ali H. Chowdhury, Ph.D., P.G.[1] and Mike J. Turco[2]

## Introduction

The Gulf Coast aquifer in Texas extends over 430 miles from the Texas-Louisiana border in the northeast to the Texas-Mexico border in the south (Figure 2-1). Over 1.1 million acre-feet of groundwater are annually pumped from this aquifer in Texas. A large portion of this water supply is used for irrigation and drinking water purposes by the fast growing communities along the Texas Gulf Coast.

The geology of the Gulf Coast aquifer in Texas is complex due to cyclic deposition of sedimentary facies. Sediments of the Gulf Coast aquifer were mainly deposited in the coastal plains of the Gulf of Mexico Basin. These sediments were deposited under a fluvial-deltaic to shallow-marine environments during the Miocene to the Pleistocene periods. Repeated sea-level changes and natural basin subsidence produced discontinuous beds of sand, silt, clay, and gravel. Six major sediment dispersal systems that sourced large deltas distributed sediments from erosion of the Laramide Uplift along the Central and southern Rockies and Sierra Madre Oriental (Galloway and others, 2000; Galloway, 2005). Geographic locations of the various fluvial systems remained relatively persistent, but the locations of the depocenters where the thickest sediment accumulations occurred shifted at different times (Solis, 1981). Stratigraphic classification of the Gulf Coast aquifer in Texas is complex and controversial, with more than seven classifications proposed. However, Baker's (1979) classification based on fauna, electric logs, facies associations, and hydraulic properties of the sediments has received widespread acceptance. Baker (1979) classified the Gulf Coast aquifer into five hydrostratigraphic units. From oldest to youngest, these are: (1) the Catahoula Confining System, (2) the Jasper aquifer, (3) the Burkeville Confining System, (4) the Evangeline aquifer, and (5) the Chicot aquifer.

Numerous growth faults (curved faults that are syndepositional and grow with depth of burial) parallel the Gulf Coast and controlled sediment accumulation and dispersal patterns during deposition. Salt domes are more common in the northern than the southern parts of the Texas Gulf Coast. These salt domes locally penetrate shallow areas of the Gulf Coast aquifer. Rapid burial of the fluvio-deltaic sediments in the Texas Gulf Coast caused the development of overpressure zones in the subsurface. In this paper, we will describe: (1) the evolution of the Gulf of Mexico basin and associated sediments of the Texas Gulf Coast aquifer; (2) structural

---

[1] Texas Water Development Board
[2] U.S. Geological Survey Texas Water Science Center

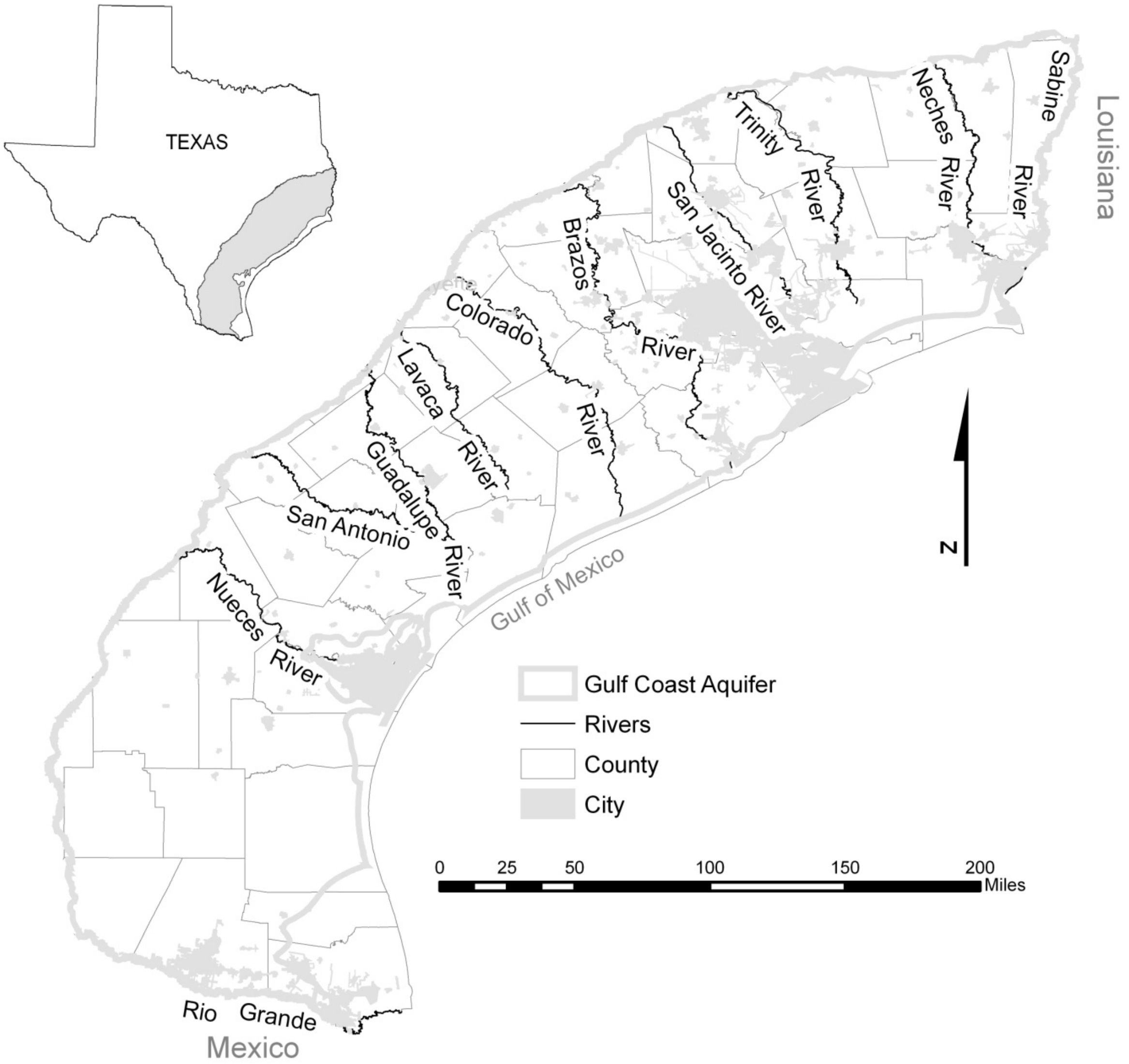

**Figure 2-1. Extent of the Gulf Coast aquifer, major rivers, and cities along the Texas Gulf Coast.**

features including faults, salt domes, and overpressure zones; (3) depositional environments; and (4) the stratigraphy of the Gulf Coast aquifer in Texas. We briefly describe geologic relationships to the occurrences of groundwater and petroleum resources in the Texas Gulf Coast.

# Physiography

The Gulf Coast aquifer in Texas is mainly covered by a smooth, low-lying coastal plain that gradually rises from sea level in the east to as much as 900 feet in the north and the west (Figure 2-2). The coastal uplands end at the contact of the Cretaceous clay and limestone where elevations rise sharply (Figure 2-2). The surficial geology of the Texas Gulf Coast is complex,

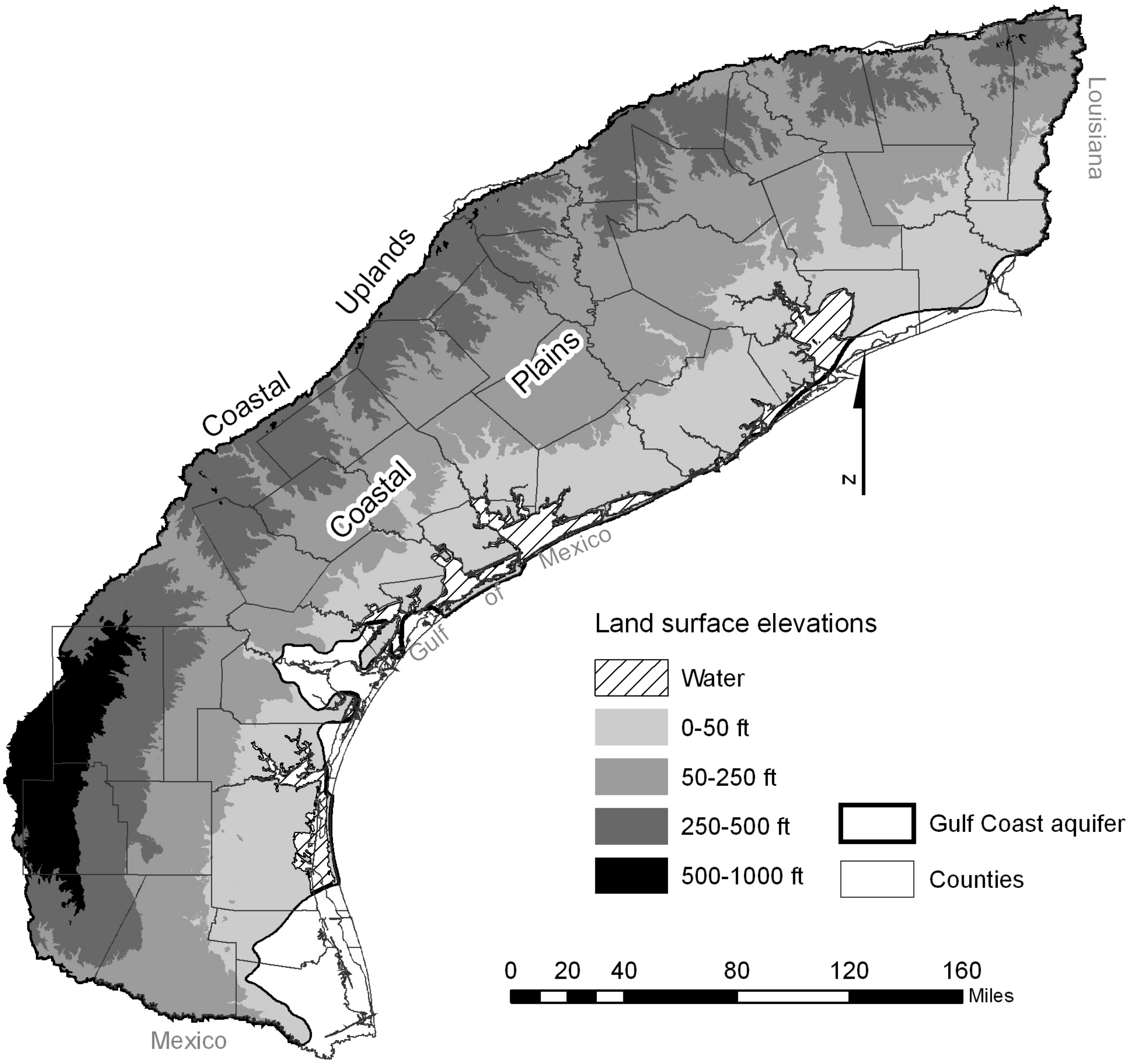

**Figure 2-2. Land surface elevation of the area directly overlying the Gulf Coast aquifer in Texas (from Texas General Land Office, http://www.glo.state.tx.us/gisdata/jpgs/elev.jpg).**

consisting of a mosaic of lithofacies with the Pleistocene and Holocene sediments covering most of the outcrop areas (Figure 2-3). The Coastal Plain is underlain by a massive thickness of sediments that form a homocline sloping gently towards the Gulf of Mexico. Several major rivers dissect the Gulf Coast aquifer and flow nearly perpendicular to the Gulf of Mexico. These rivers include the Sabine, Trinity, Colorado, Guadalupe, Brazos, San Antonio, and Rio Grande (Figure 2-1). Between the valleys of the major rivers crossing the coastal plains, differential erosion of the softer and harder beds led to the formation of parallel low ridges and escarpments. These features provided the lowlands with a distinctive topographic belt. This "belted"

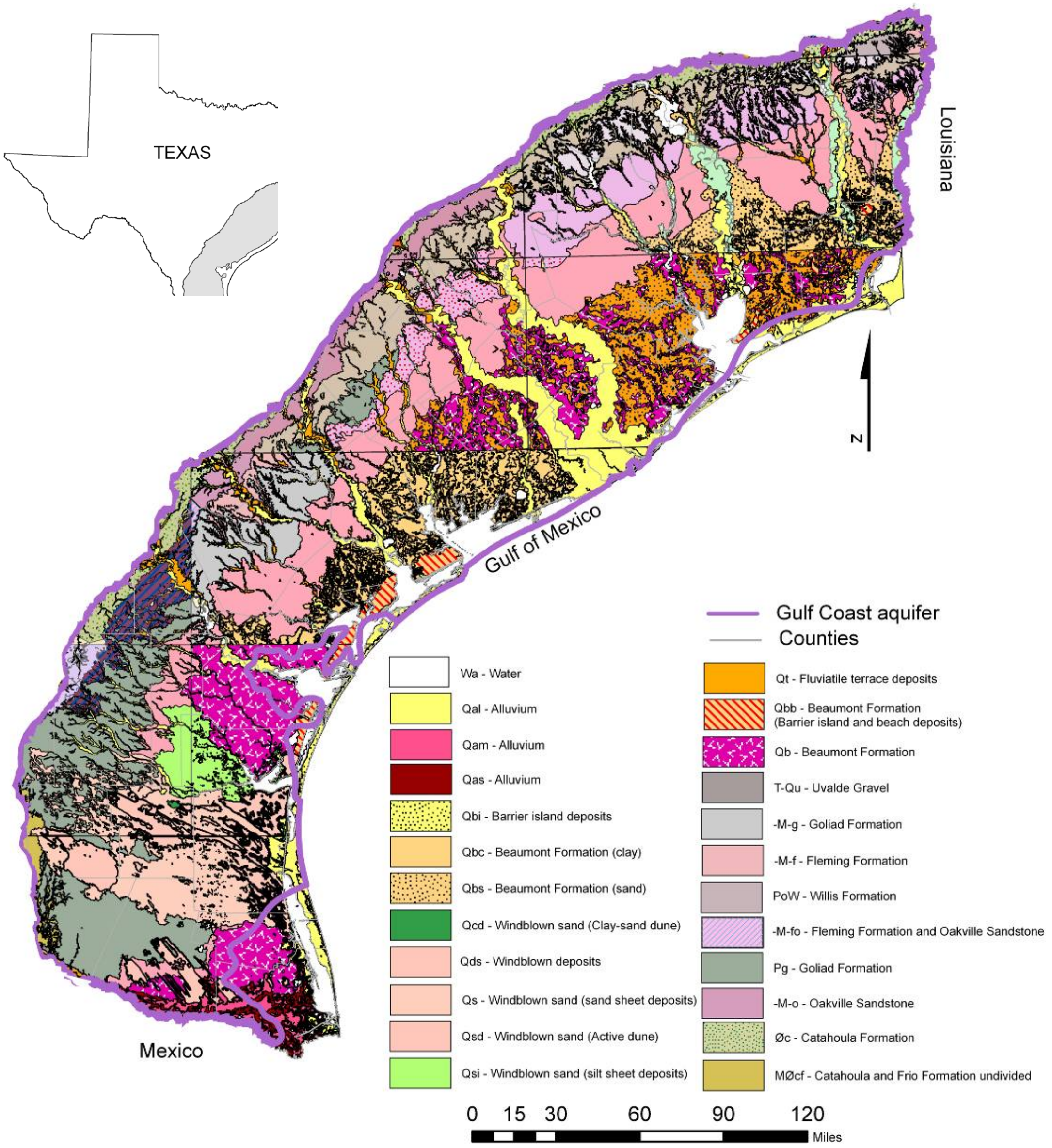

**Figure 2-3.** **Surficial geology of the Gulf Coast aquifer in Texas (Aronow and Barnes, 1968; Shelby and others, 1968; Proctor and others, 1974; Aronow and others, 1975; Aronow and Barnes, 1975; Brewton and others, 1976a; Brewton and others, 1976b).**

topography is better developed in East Texas and is less evident in South Texas due to increased aridity and the influence of the Sierra Madre Oriental in Mexico (Bryant and others, 1991). Most of the major rivers that arise farther away from the coastal plains have broad alluvial valleys and deltaic plains and empty sediment loads directly into the Gulf of Mexico. The smaller rivers have narrow valleys and drain into estuaries or lagoons that are disconnected from the Gulf by onshore barrier islands or offshore bars. Long barrier islands with few tidal inlets and adjoining lagoons parallel part of the Texas Gulf Coast. Padre Island, with a length of about 130 miles, is the longest barrier island adjacent to the Gulf of Mexico.

The Gulf Coast aquifer in Texas outcrops over a large geographic area located between 18°N and 31°N latitudes. Therefore, the climate varies widely, from humid in the north to semi-tropical to semi-arid in the south. Annual rainfall ranges from about 56 inches in the north to about 18 inches in the south. The mean annual temperature ranges from about 60° F in the north to about 70° F in the south. Annual pan evaporation rates range from about 60 inches in the north to 100 inches in the south (Williamson and Grubb, 2001).

# Basin evolution and structural features

Sediments of the Texas Gulf Coast aquifer were deposited in the coastal plains of the Gulf of Mexico Basin (Figure 2-4) during the Tertiary and Quaternary periods. The Gulf of Mexico Basin was formed by the downfaulting and downwarping of Paleozoic basement rocks during the break-up of the Paleozoic megacontinent Pangaea and the opening of the North Atlantic Ocean in the Late Triassic (Byerly, 1991; Hosman and Weiss, 1991). Igneous processes played a significant part in the evolution of the Gulf of Mexico basin, as observed from the presence of

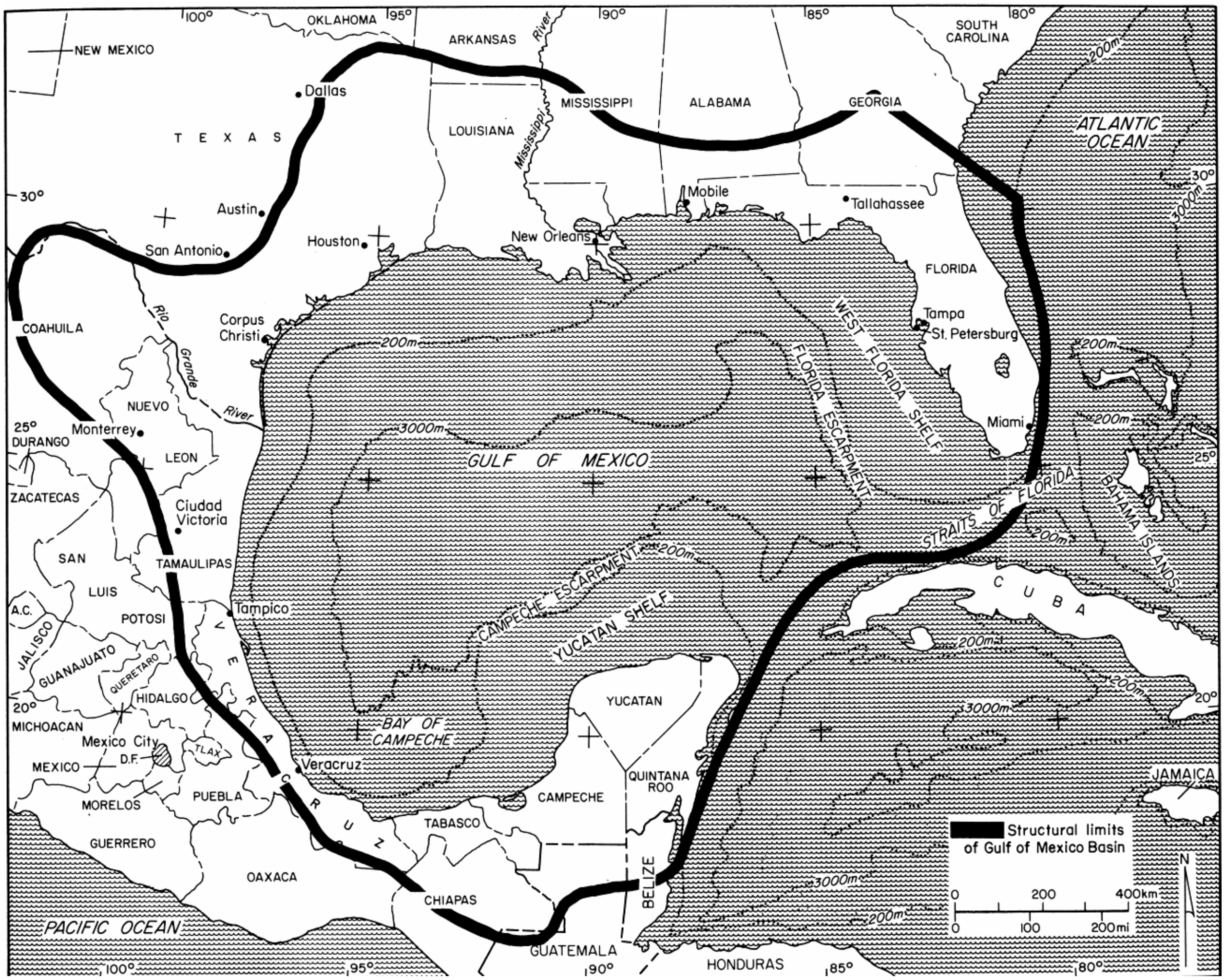

Figure 2-4. Geographic extent of the Gulf of Mexico Basin (from Salvador, 1991).

basaltic rocks in rift basins around the Gulf of Mexico margins. Igneous processes may have partly controlled thermal and uplift history of the Gulf of Mexico basin (Byerly, 1991). Most of the igneous activity occurred in the Late Cretaceous and Oligocene-Miocene periods, although activity continues today in the western part of the Gulf of Mexico basin in Mexico (Byerly, 1991). Local structures that rim the Gulf of Mexico basin are primarily formed by gravity acting on thick sedimentary sections deposited on abnormally pressured shale or salt that sole out above the basement to produce salt-flow structures and growth faults (Figure 2-5) (Nelson, 1991).

The Balcones and Luling-Mexia-Talco fault zones rim the basin and form a divide between Upper Cretaceous and Eocene strata (Figure 2-6) (McCoy, 1990). The Balcones fault zone is dominated by normal faults that run parallel to the trend of the Ouachita orogenic belt. Along these faults, sediments have been displaced up to 1,500 feet, shifting downward toward the Gulf of Mexico. Where the faults juxtapose against the resistant Lower Cretaceous and more resistant Upper Cretaceous sediments, it forms the Balcones Escarpment (Ewing, 1991). The Luling-Mexia-Talco fault system consists of three segments of symmetric grabens linked by deep en-echelon normal faults and extends from Central Texas to the Arkansas border (Ewing, 1991). Movement along the faults began in the Jurassic, as evidenced by thick sediment piles in the grabens, and continued later movement is supported by offsets of Paleocene beds. Many of the local structures, including the Sabine Arch, Houston Embayment, San Marcos Arch, Rio Grande Embayment, salt domes, and numerous northeast-southwest trending growth faults, began to form prior to the Tertiary period (Figure 2-5). The growth faults have an extensional component and are often referred to as listric-normal faults (listric from Greek for “shovel” to describe curved fault planes) (Figures 2-7 and 2-8) (Nelson, 1991). Bornhauser (1958) suggested that most of the regional structures, embayments, arches, and flexures were created by a combination of differential subsidence of the basin floor and thick sediments that flowed as viscous fluids on sloping surfaces. Others suggested that deep-seated vertical intrusions of salt in the form of narrow ridges pushed up the gulf-ward dipping beds to form deep-seated anticlines (Quarles, 1952; Cloos, 1962). These structural features controlled sediment accumulation patterns, as supported by the observation that bedding commonly thins towards and over the arches and thickens in the embayments (Grubb, 1998). All regional and local structures in the Texas Gulf Coast were developed by shallow tectonics in rapidly subsiding basins, which caused sediments to be buried to considerable depths (Bornhauser, 1958) while still preserving most of their initial porosity. If the sediments were affected by deeper tectonic events, a higher temperature associated with metamorphic processes would have destroyed most of the transmissive capacities of the sandstone.

The Sabine Arch lies between the East Texas and North Louisiana basins (Figure 2-5), and its boundaries are gentle homoclines into the surrounding basins. The uplifted area contains a thin layer of Jurassic salt that forms low amplitude swells (Ewing, 1991). In the mid-Cretaceous, the Sabine Uplift area was uplifted and subsequently eroded to form the clastic sediments of the Woodbine Formation. The Woodbine Formation was uplifted again and the sediments were subsequently eroded and deposited before the formation of the Austin Chalk (Halbouty and Halbouty, 1982). A third episode of uplift during the Eocene provided the current outcrop pattern around the Sabine arch (Ewing, 1991).

The San Marcos arch is a broad area of lesser subsidence and is a subsurface extension of the Llano Uplift, which contains exposed Precambrian Rocks. The arch is located between the Rio

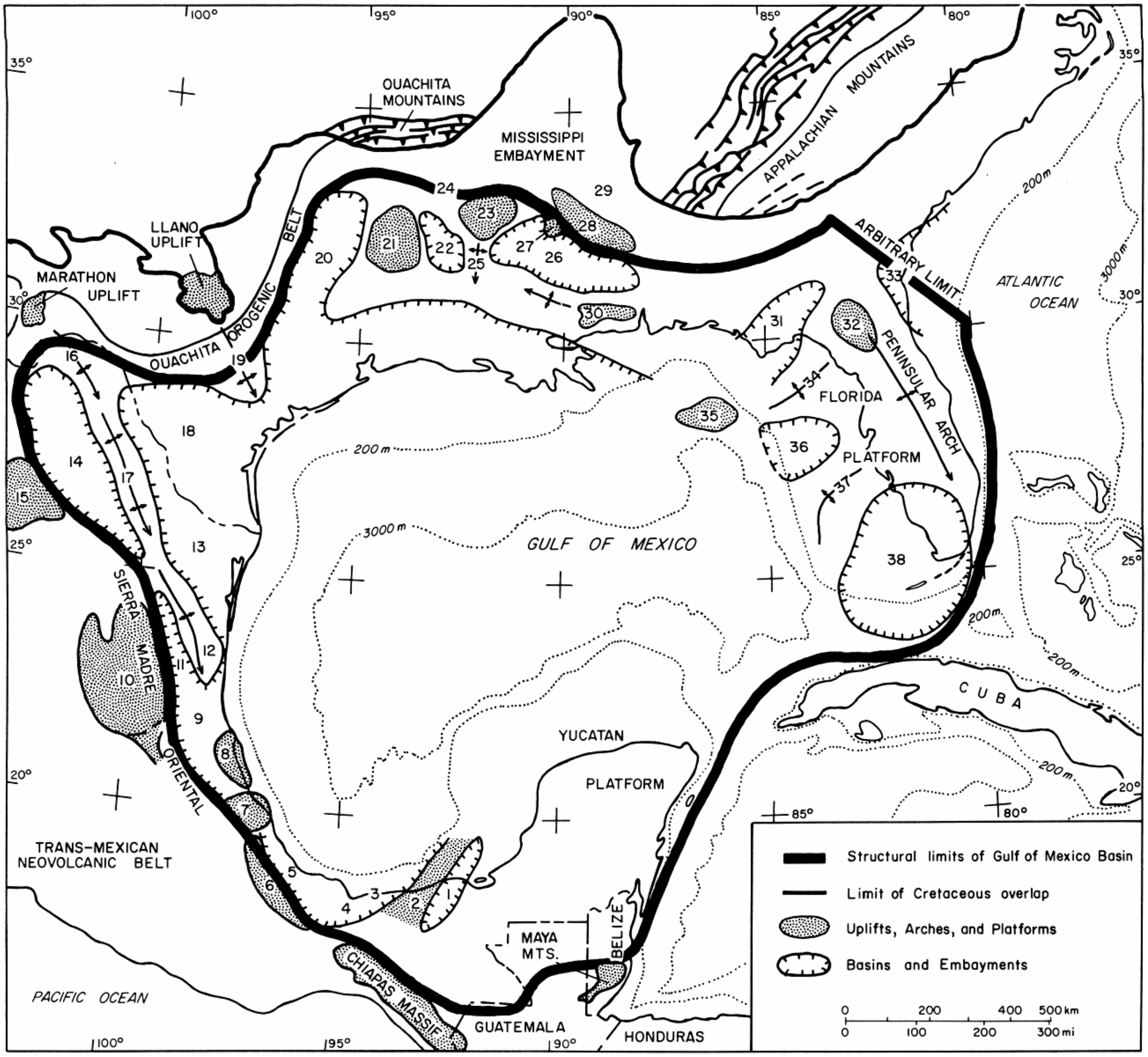

Figure 2-5. Structures in the Gulf of Mexico Basin include the: (1) Macuspana basin, (2) Villahermosa uplift, (3) Comalcalco basin, (4) Isthmus Saline basin, (5) Veracruz basin, (6) Cordoba platform, (7) Santa Ana massif, (8) Tuxpan platform, (9) Tampico-Misantla basin, (10) Valles-San Luis Potosi platform, (11) Magiscatzin basin, (12) Tamapulias arch, (13) Burgos basin, (14) Sabinas basin, (15) Cohuila platform, (16) El Burro uplift, (17) Peoytes-Picachos arches, (18) Rio Grande embayment, (19) San Marcos arch, (20) East Texas basin, (21) Sabine uplift, (22) North Louisiana salt basin, (23) Monroe uplift, (24) Desha basin, (25) La Salle arch, (26) Mississippi salt basin, (27) Jackson dome, (28) Central Mississippi deformed belt, (29) Black Warrior basin, (30) Wiggins uplift, (31) Apalachicola embayment, (32) Ocala uplift, (33) Southeast Georgia embayment, (34) Middle Ground arch, (35) Southern platform, (36) Tampa embayment, (37) Sarasota arch, and (38) South Florida basin (from Salvador, 1991).

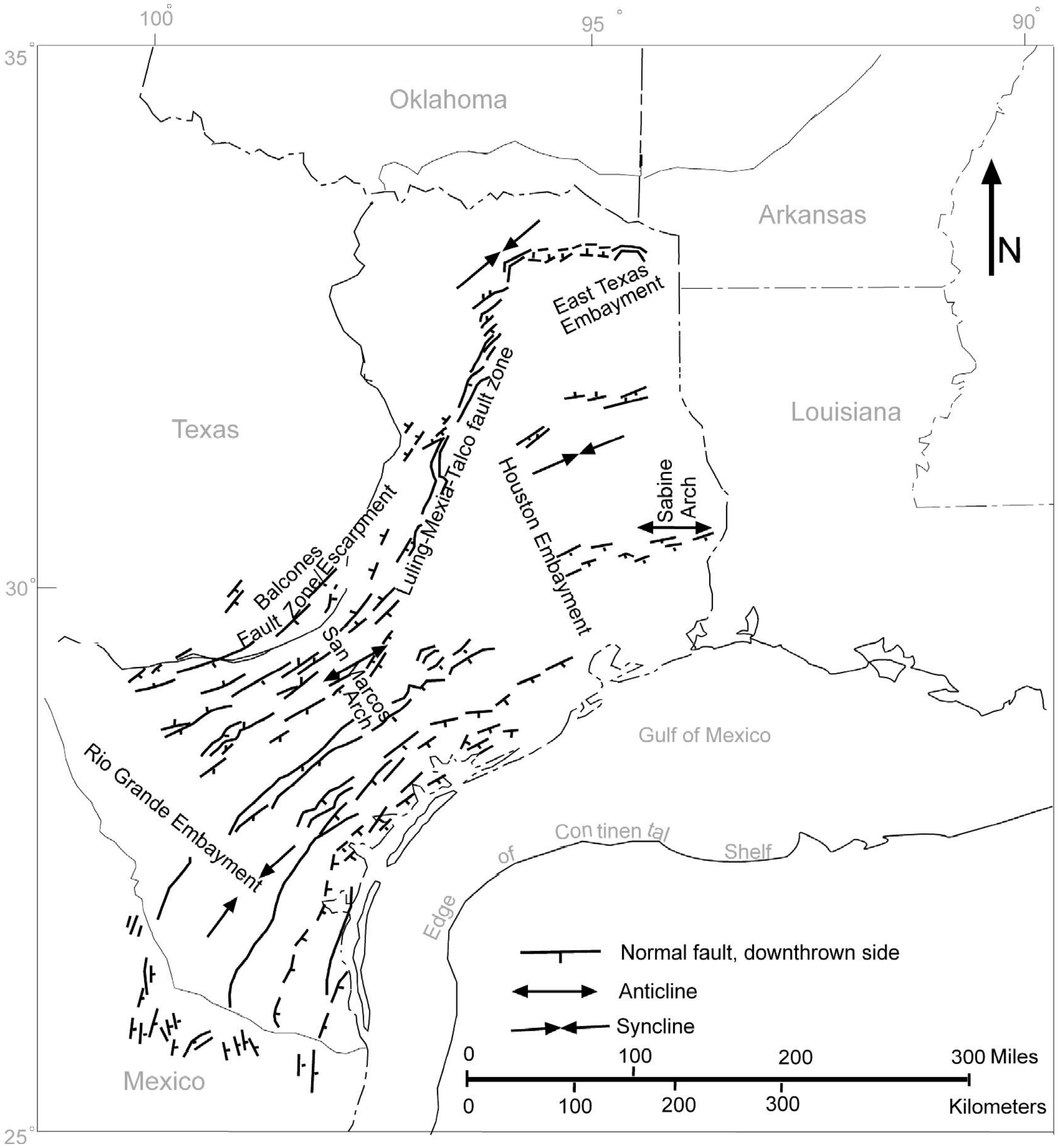

**Figure 2-6.** **Map showing locations of faults in the Gulf Coast aquifer in Texas. Note that most of the faults have extensional components and occur parallel to the coast. Only structural features for Texas are shown (modified from Murray, 1961 and Hosman, 1996).**

Grande Embayment and East Texas Basin (Figure 2-5). The arch is crossed by the basement involved normal faults of the Balcones-Lulling fault zone that parallels the buried Ouachita Orogenic Belt (Ewing, 1991).

The Rio Grande embayment is a small deformed basin showing signs of compression during the Laramide orogeny in the Late Cretaceous–Paleogene. The embayment lies between El Burro uplift in Northeast Mexico and the south of the basin-marginal Balcones fault zone (Figure 2-5) (Ewing, 1991). It contains few Jurassic salt domes, but salt tectonics is a minor component of the basin history. Jurassic and Cretaceous sedimentation were continuous and recorded a general subsidence and transgression in the Early Cretaceous (Ewing, 1991).

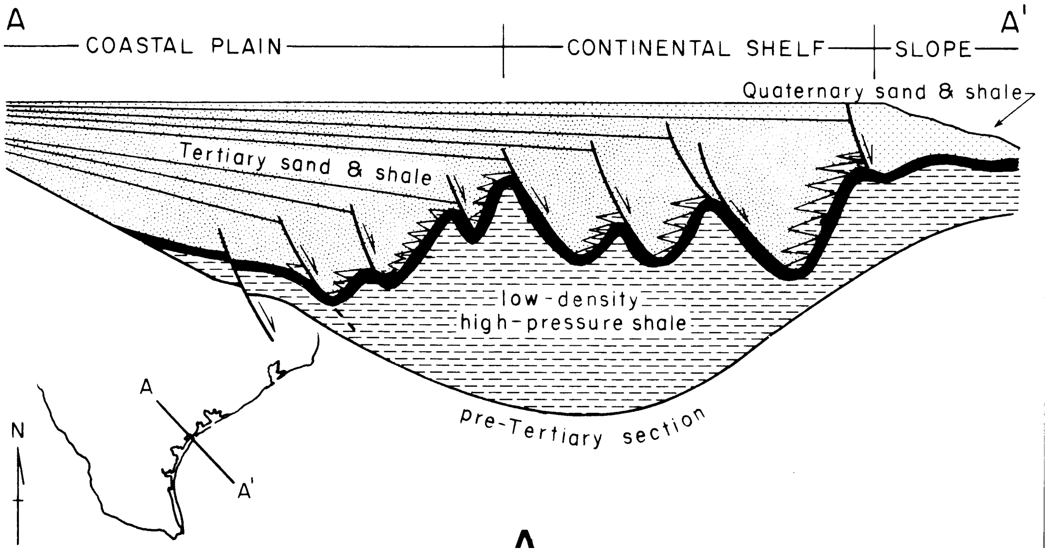

**Figure 2-7. Diagrammatic cross-section along the central part of the Texas Gulf Coast and northern Gulf of Mexico basin showing depositional and structural styles exhibited by fluvial-deltas (from Bruce, 1973 and Solis, 1981).**

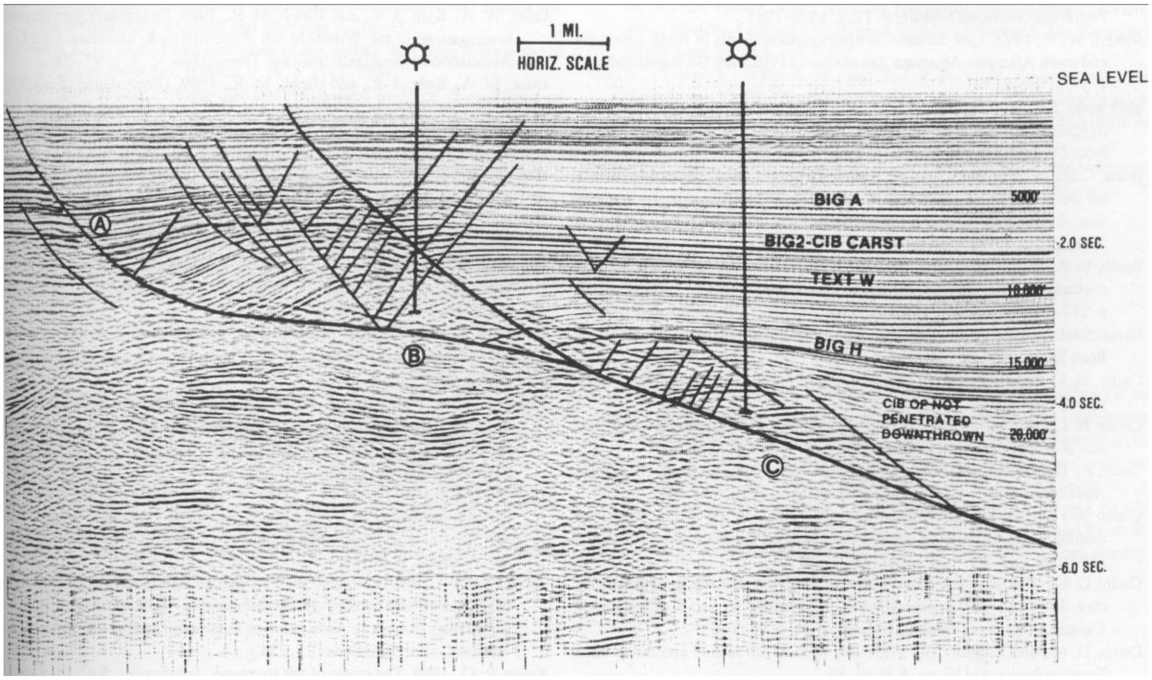

**Figure 2-8. An example of a growth fault in the Gulf Coast across Corsair fault trend, offshore Texas. This seismic section shows a listric segment of the fault (A), a bedding parallel slide surface that rests on overpressured shale (B), and a deep ramp that changes orientation of the slide surface (from Vogler and Robinson, 1987).** ***Reprinted by permission of the AAPG whose permission is required for further use.***

The strike-oriented growth faults found in the Texas Gulf Coast aquifer occur parallel to the coastline (Figure 2-6). More than 150 faults have been identified in the Houston metropolitan area alone (Verbeek and others, 1979). Most of these faults are rooted in the deeper subsurface at depths of 3,200 to 13,000 feet (Verbeek and others, 1979). These growth faults have throws that increase with depth and strata are thicker on the downthrown side than on the upthrown side (Figures 2-7 and 2-8). Growth faults in the Texas Gulf Coast may be caused by a number of processes, including a buoyant rise of salt or shale, differential sediment loading (prograding deltaic sand on prodelta mud), differential compaction leading to varying volumes of rock bodies (differential strain along surfaces where facies change), and free gravity gliding (stiff rock overlying soft rock such as evaporites) (Jackson and Galloway, 1984). In the Texas Gulf Coast aquifer, abrupt changes in sediment thickness occur locally over short lateral distances between growth faults (Verbeek and others, 1979). Kreitler and others (1977) reported appreciable vertical displacement and an abrupt thickening of the Alta Loma Sand at the base of the Chicot aquifer in Harris and Galveston counties that they attributed to faults. Solis (1981) constructed sand percentage maps using spontaneous and resistivity logs and concluded that faults have strongly influenced distribution and orientation of Miocene to lower Pleistocene depocenters containing the thickest sand-bearing unit. Sand depocenters commonly developed on the downthrown fault blocks parallel to and/or bounded by strike-oriented faults (Solis, 1981). Solis (1981) noted four principal types of variations in the occurrences of the base of the fresh water-saline water interface: (1) it is deeper on the basinward side of some growth faults than on the landward side, (2) it is shallower on some downthrown fault blocks, (3) it rises to shallower depths where sand bodies pinch out, and (4) it rises around salt domes. The role of many of these faults in controlling regional groundwater flow remains uncertain, as throws across the faults are not large enough to totally offset the hydrogeologic units (Hosman and Weiss, 1991). However, the fault zones may partially compartmentalize groundwater flow systems locally, as seen from varying groundwater compositions across the fault zones (Kreitler and others, 1977). Some of the faults in the Texas Gulf Coast are still active and moving at rates of 0.2 to 0.8 inches per year (Shah and Lanning-Rush, 2005).

Salt domes are more common in the northern than the southern part of the Texas Gulf Coast (Morton and others, 1983). Some of these salt domes locally penetrate areas of the shallow aquifer (Figure 2-9). The source of the salt is the Jurassic Louann salt. The salt could rise up in the form of spires, banks, and domes due to: (1) massive accumulation of thick coarser, dense sediments by prograding deltas on earlier formed pro-delta muds; (2) gravity-spreading of thick salt mass basinward; (3) thermal convection; and (4) buoyancy (Figure 2-10) (Jackson and Galloway, 1984; Williamson and Grubb, 2001). Jackson and Galloway (1984) reported that salt domes have constituted the most important play in the Texas Gulf Coast since the discovery of Spindletop south of the town of Beaumont in 1901 (Jackson and Galloway, 1984), which produced more than 100,000 barrels per day (Spearing, 1991). Salt domes provide both structural and stratigraphic traps for oil and gas. Potential traps are present wherever sand prevails over mud and carbonates with enhanced porosity prevail over those with normal porosity (Jackson and Galloway, 1984). In addition, salt domes may cause deterioration in groundwater quality in surrounding areas (Chowdhury and others, this volume).

Rapid accumulation of sediments fed by large river systems into deltas led to the formation of overpressure zones where fluid pressures are substantially higher than hydrostatic pressures (Jones, 1969). Rapid burial of the sediments restricted expulsion of pore water, building up fluid

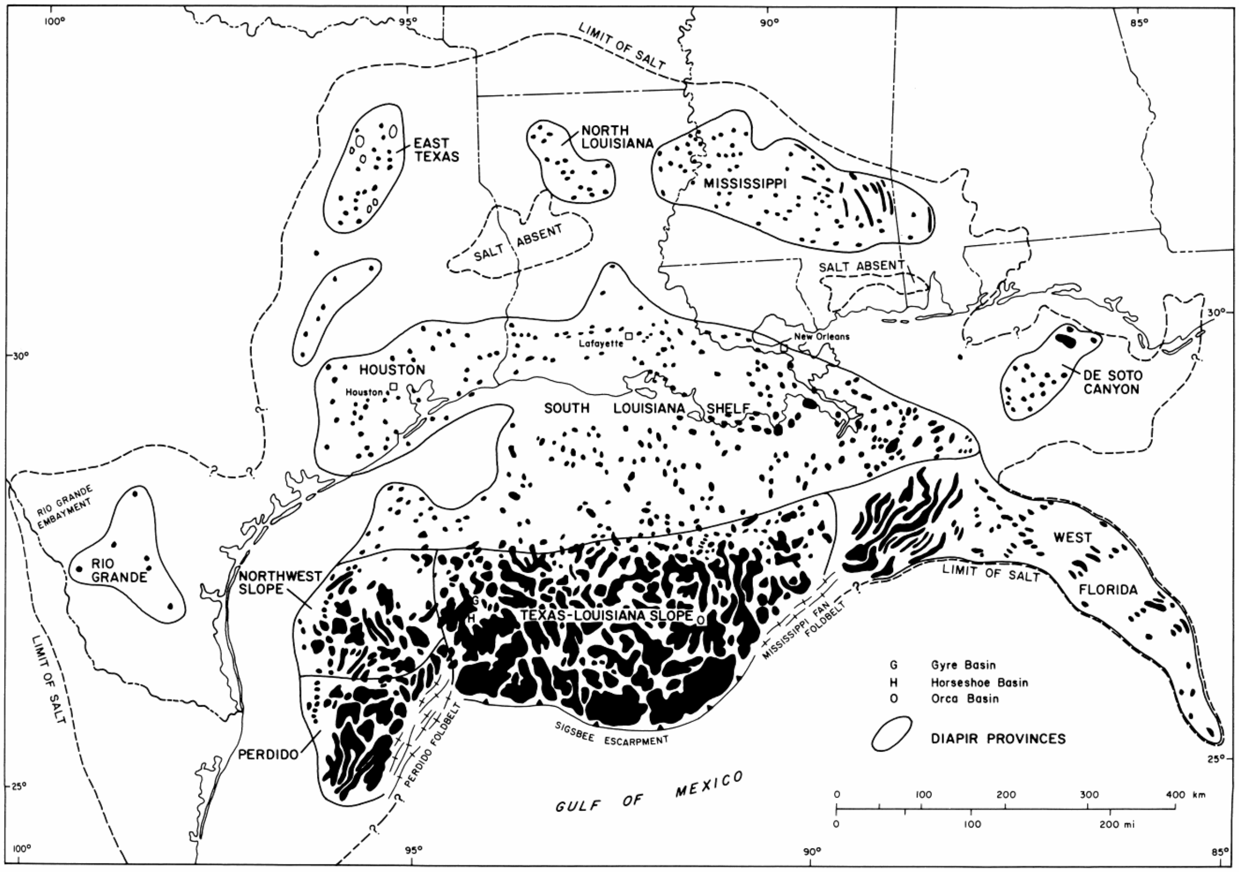

**Figure 2-9. Map showing locations of salt deposits in the Gulf of Mexico basin (from Ewing, 1991). Note distribution of salt in the Rio Grande embayment, northeastern part of the Texas Gulf Coast including Houston area, and East Texas. Salt deposits occupy a much wider area in the offshore, in the northwest slope and Texas-Louisiana slope of the Gulf of Mexico basin.**

pressures and undercompacting the sediments (Williamson and Grubb, 2001). Under overpressure conditions, shale layers act as detachment planes for faults and often provide habitat for significant hydrocarbon accumulations (Mukherji and others, 2002). For example, nearly half of the gas production in the Tertiary units from southern part of Louisiana come from the approximately 1,800 foot section around the top of overpressure zones (Leach, 1994). In addition, groundwater flow in the Gulf Coast aquifer is further complicated by numerous clay lenses less than six feet thick contained within the water-bearing units of the sand beds that retard vertical movement locally and may provide different hydraulic heads to each sand bed (Gabrysch, 1984).

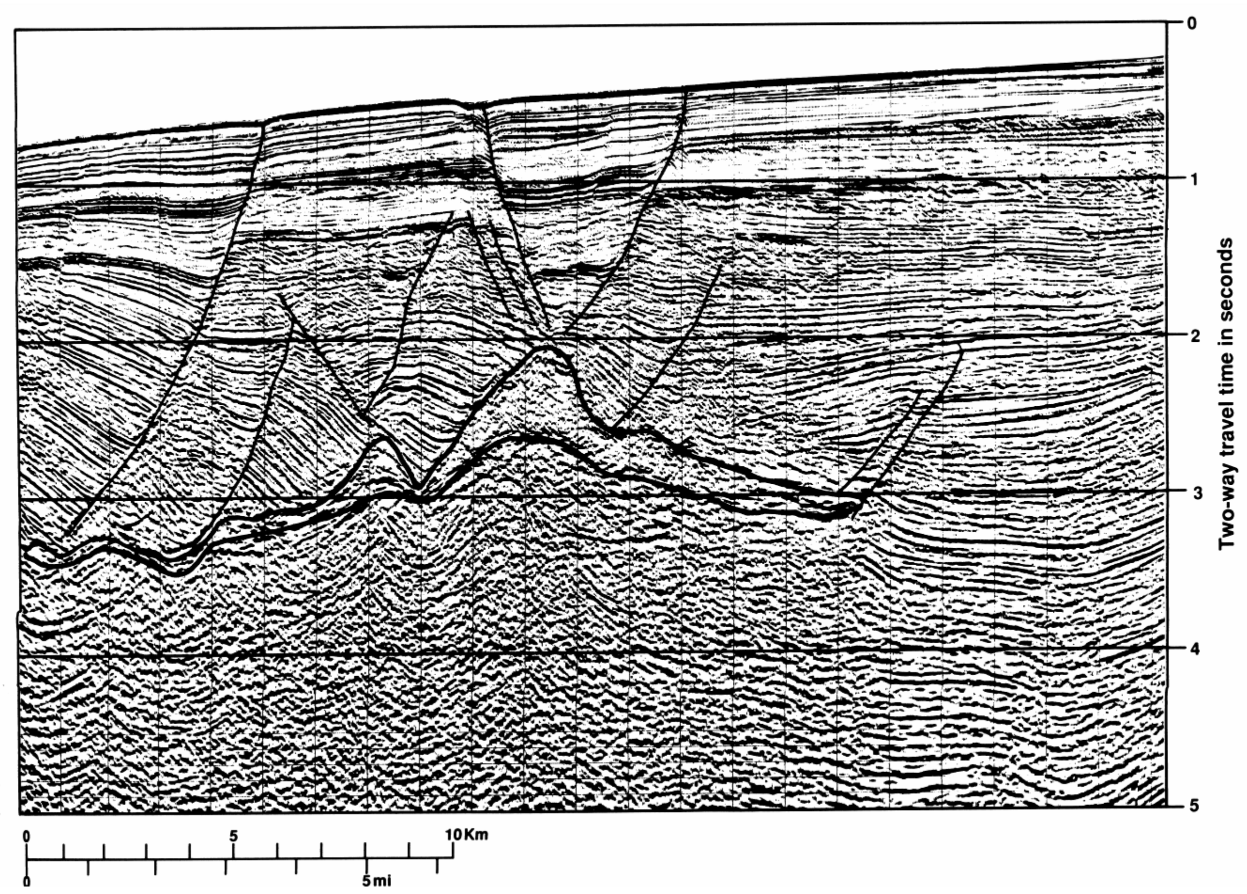

**Figure 2-10. Seismic section across the updip limits of a thin salt sheet. Deformation caused by gravity spreading of the salt and listric-normal faults developed in the overlying section as a result of movement of the salt (from Ewing, 1991).**

# Depositional Environment

Deposition in the Gulf of Mexico basin was affected by crustal subsidence, sediment dispersal from areas as far away as Trans-Pecos Texas beyond the Gulf Coastal Plain, and eustatic changes in sea level (Figure 2-11) (Galloway, 1989). Most of the early Cenozoic depositional episodes were derived from erosion of the Laramide uplift along the central and southern Rockies and Sierra Madre Oriental in northern Mexico. Late Eocene through to early Oligocene crustal heating, volcanism, and subsequent erosion of much of central Mexico and the southwestern United States nourished Oligocene through early Miocene depositional episodes (Galloway and others, 2000; Galloway, 2005). Pliocene uplift and tilting of the western High Plains further rejuvenated northwestern sediment sources from the Rocky Mountains (Galloway, 2005). Galloway (2005) identified the predominant sediment source areas for the fluvial-deltaic and shore-zone depositional systems in the Coastal Plains and the northern part of the Gulf of Mexico Basin (Figure 2-11).

Sediments of the Gulf Coast aquifer were deposited in a fluvial-deltaic or shallow-marine environment (Sellards and others, 1932). Repeated sea-level changes and basin subsidence

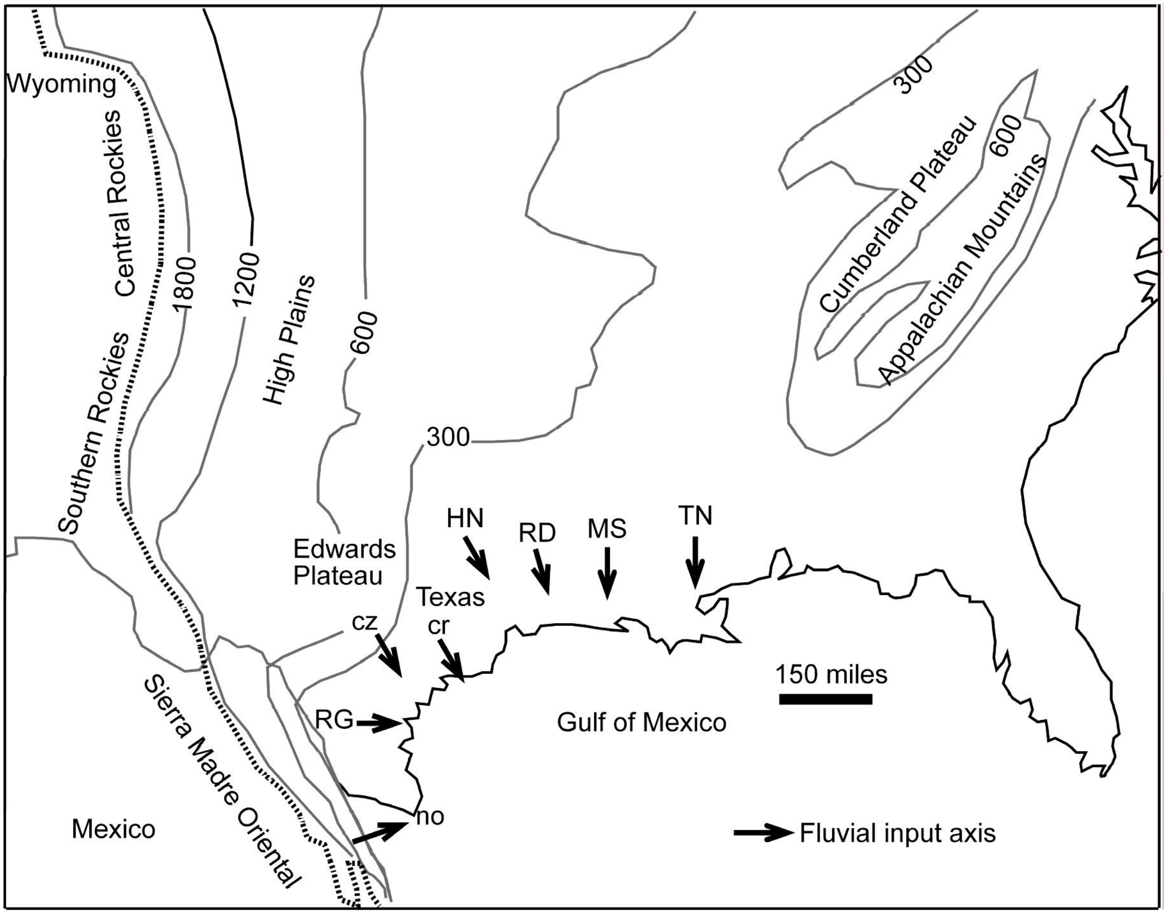

**Figure 2-11. Principal sediment dispersal systems for the Cenozoic sediments of the Gulf of Mexico basin. Contours (in feet) indicate modern elevations of the uplands. Fluvial axes no=Norias, RF=Rio Grande, cz=Carrizo, cr=Corsair, HN=Houston, RD=Red River, MS=Mississippi, TN=Tennesse (after Galloway, 2005).**

caused the development of cyclic sedimentary deposits composed of discontinuous sand, silt, clay, and gravel (Sellards and others, 1932; Kasmarek and Robinson, 2004). Changes in sea level and sediment source areas gave rise to a heterogeneous assemblage of river, windblown, and lake sediments onto a delta (Galloway, 1977). Inland, closer to sediment source areas, coarser fluvial and deltaic sand, silt, and clay sediments predominate, while offshore they grade into mainly finer brackish and marine sediments. Isostatic adjustment caused subsidence of the basin and a simultaneous rise of the land surface, which resulted in a progressive thickening of the stratigraphic units towards the gulf. Progressively younger sediments outcrop towards the coast. The older Eocene- to Miocene-aged sediments in the western portion of the study area are comprised of thickly-bedded fluvial sands. These sands are occasionally interbedded with tuffaceous ash that was probably derived from source areas in the Davis Mountains and other volcanic centers in Trans-Pecos Texas (Sellards and others, 1932).

Galloway and others (2000) compiled eighteen major depositional episodes in the Gulf of Mexico basin using lithofacies, thickness, stratigraphic architecture, and facies association maps. For the northern and central portion of the Texas Gulf Coast, they identified six sediment dispersal systems that sourced large deltas named Norias, Rio Grande, Carrizo, Corsair, Houston, Red River and related shore zone, shelf, and basinal systems (Figure 2-11). Two prominent fluvial-dominated delta systems, the Houston delta and the Holly Spring delta, established sediment dispersal patterns in the northern Gulf Coast (Fisher and McGowen, 1967; Galloway, 1968; Xue and Galloway, 1993). The Houston delta is the largest and sandiest and is fed by bed-load fluvial systems. The smaller Holly Springs delta is separated from the Houston delta by a broad shore-zone system. The Rio Grande axis lies within the Rio Grande embayment and the Houston axis is centered within the Houston basin. The Rosita and Corsair systems encroached onto the San Marcos arch in central Texas. Clastic sediment contribution declined and carbonate accumulation continued for most of the southeastern gulf (Yucatan platform) throughout the Cenozoic (Galloway and others, 2000). During the late Pliocene and Pleistocene, climatically enhanced runoff and erosion in the southern Rocky Mountain uplands rejuvenated sediment supply through the Rio Grande drainage network (Galloway, 2005).

Solis (1981) studied the Pliocene–Pleistocene sections of the central part of the Texas Gulf Coast. He concluded that geographic locations of the various fluvial systems remained relatively persistent, but the locations of the depocenters shifted at different times. For example, depocenters shifted from the present-day locations of Jackson, Matagorda, Wharton, and Victoria counties to Refugio, Calhoun, and Aransas counties during the deposition of the lower Fleming and the Goliad and the Willis sands (Solis, 1981).

Sediments of the Chicot, Evangeline, and Jasper aquifers and the Burkeville confining system were deposited on steep slopes dipping toward the gulf. The dip of the beds is nearly perpendicular to the coastline. Slopes of the bases of the aquifers are highly variable with abrupt changes observed between nearby wells (Chowdhury and Mace, 2003). The deeper aquifers generally have a base with higher slopes than the shallower aquifers. The steep slopes of the aquifers were probably caused by a combination of growth faulting and deep-seated movements of salt domes. The Burkeville confining system and the Jasper aquifer host irregular bottoms that locally thicken to develop sediment wedges. Near the coastline in the southern part of the Texas Gulf Coast, the bottom of the Chicot aquifer lies at an elevation of -1,200 feet, the bottom of the Evangeline aquifer at an elevation of -2,600 feet, the bottom of the Jasper aquifer at an elevation of -8,000 feet, and the bottom of the Burkeville confining system at an elevation of -5,000 feet (Chowdhury and Mace, 2003).

Sediment thickness increases from the west to the east towards the Gulf of Mexico. Thickness maps for the aquifers show a maximum thickness of 1,200 feet in the Chicot aquifer, 2,800 feet for the Evangeline aquifer, 3,200 feet for the Jasper aquifer, and 1,600 feet for the Burkeville confining system in the southern part of the Gulf Coast (Chowdhury and Mace, 2003). While all east-west cross sections show a general thickening of the aquifers down-dip towards the Gulf of Mexico, the aquifers are relatively uniform in thickness from north to south.

Occurrences of numerous paleo-caliche horizons (calcium carbonate that occur between interstitial pores from near surface evaporation of groundwater) in the Gulf Coast aquifer sediments indicate that a consistently dry condition perturbed the more humid climate during deposition in the Miocene and the Pleistocene periods (Galloway, 1977).

# Stratigraphy

In the Texas Gulf Coast, considerable heterogeneity of the sediments, discontinuity of the beds, and a general absence of index fossils and diagnostic electric log signatures in the subsurface often make correlation of the lithologic units difficult. Since 1903, at least seven stratigraphic classifications have been proposed (Kreitler and others, 1977). Guevera-Sanchez (1974) identified only the Beaumont and undifferentiated Lissie-Willis sands in the subsurface. Rose (1943a) classified the upper Miocene and Pliocene-Pleistocene sediments into seven zones based on permeability and sand percentage. The most permeable and heavily pumped Alta Loma Sand lies within zone 7 (Rose, 1943b). Wood and others (1963) considered the Beaumont Clay as a confining unit that extends from the land surface to the top of the Alta Loma Sand. Jorgensen (1975) classified Rose’s zones into the Chicot aquifer, with the Alta Loma Sand at its base, and defined the underlying units as the Evangeline aquifer.

From oldest to youngest, he classified the Tertiary rocks into the Frio Formation, the Anahuac Formation, and the Catahoula Tuff or Sandstone (early Miocene); the Oakville Sandstone and the Fleming Formation (mid- to late-Miocene); the Goliad Sand (Pliocene); the Willis Sand, Bentley Formation, Montgomery Formation, and Beaumont Clay (Pleistocene); and alluvium (Holocene) (Baker, 1979) (Figure 2-12). The Catahoula Tuff or Sandstone, Goliad Sand, Willis Sand, and Beaumont Clay are often interchangeably referred to in the literature as formations (Sellards and others, 1932; Baker, 1979). Given the complexity of identifying the base of the Pleistocene from electric logs, several nomenclatures have been used to characterize these sediments. For example, Solis (1981) defined the base of the Pleistocene to be represented by the Lissie Formation. The undifferentiated Lissie Formation has also been considered equivalent in age to the Montgomery and the Bentley formations with the bottom of the latter being considered the base of the Pleistocene (Dutton and Richter, 1990). The Montgomery Formation is also occasionally included within the Beaumont Clay (Baker and Dale, 1961). In place of the Montgomery and the Bentley formations, the undifferentiated Lissie Formation of equivalent age occurs in the Lower Rio Grande Valley (Baker and Dale, 1961; Bureau of Economic Geology, 1976). The stratigraphic section of Baker (1979) is the basis for the summary information that follows.

## Oligocene Series

Although some controversy exists in the literature, the Oligocene-aged sediments constitute the base of the Gulf Coast aquifer in Texas. The contact between the Oligocene-aged sediments and the underlying Eocene-aged sediments is mostly indistinguishable based solely on lithology. Paleontological differences associated with the Oligocene and Eocene Series are more commonly used to identify the difference between the two units. Throughout the entire extent of the Gulf Coast aquifer, most of the marine deposits in the lower part of the Oligocene belong to the Vicksburg Group or equivalent strata (Hosman, 1996). The Vicksburg Group is a regional confining unit that separates the Coastal Uplands aquifer system from the Coastal Lowlands aquifer system and consists primarily of marine clays and thin-bedded sandstones of the Eocene-aged Jackson Group and the Oligocene-aged Frio Clay, or Frio Formation, in the subsurface. Above this predominantly marine sequence that lies in the lower part of the Oligocene deposits,

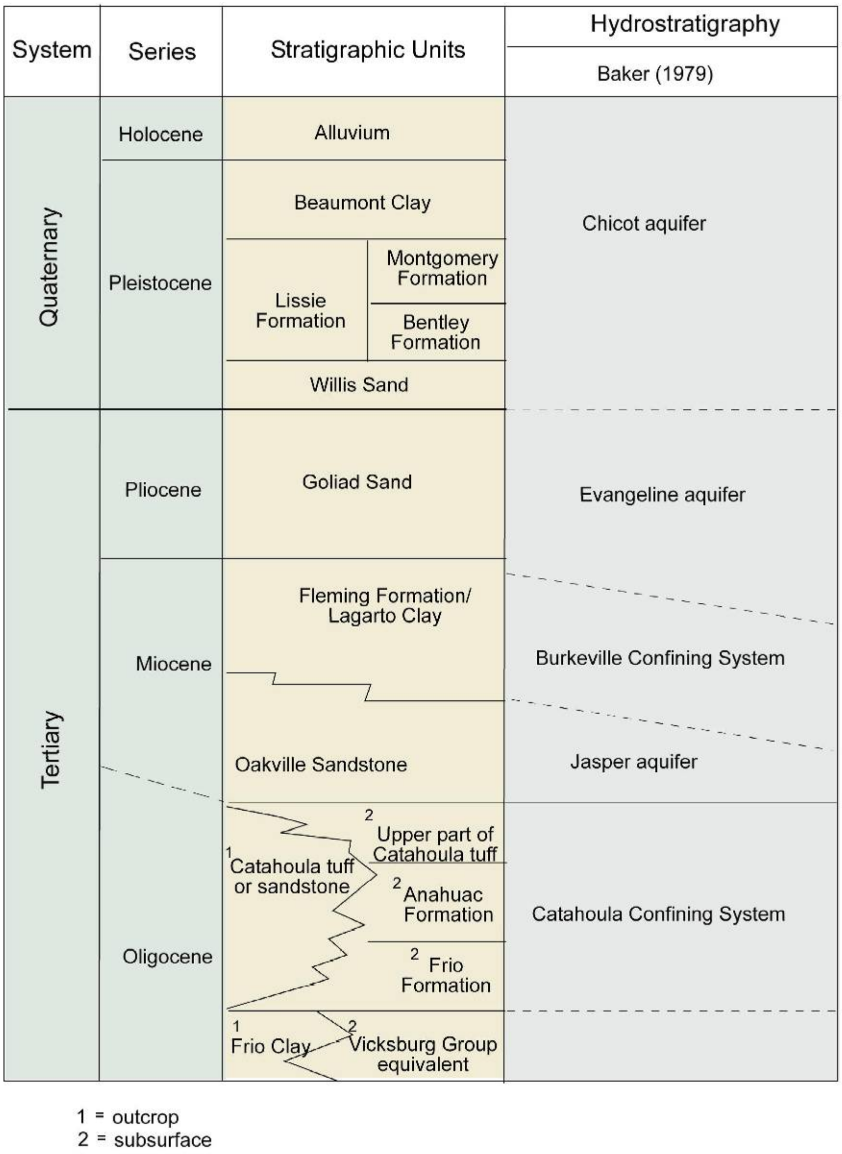

**Figure 2-12. Stratigraphic column showing sediment successions formed during the Oligocene to the Pleistocene periods. Hydrostratigraphic divisions for corresponding stratigraphic units are indicated (after Baker, 1979).**

the sediments become more arenaceous (sandier) and contain higher amounts of volcanic tuffaceous sandstones and bedded tuff in South Texas (Hosman, 1996).

The age of the Frio Formation has been debated for many years, but for the purpose of this paper, we consider it to lie at the base of the Oligocene sequence. The Frio Formation is an assemblage of sediments that are almost entirely composed of dark, greenish-gray colored clays above the Eocene-aged Fayette sands in South Texas (Sellards and others, 1932). The clays can be gypsiferous, laminated, and interbedded with sandy clays, sands, and sandstone. Silicious and calcareous concretions can occur in the sediments and the sediments are not generally fossiliferous. The thickness of the formation in outcrop varies from about 150 feet to 800 feet, whereas beneath the surface the thickness ranges from 250 feet to 600 feet (Sellards and others, 1932). The lack of sand and fossils in the sediments suggest that the adjoining land masses were low and near sea level during deposition and that the clays may have had a fresh-water origin.

The Catahoula Formation unconformably overlies the Frio Formation, which is unconformably overlain by the Oakville Formation (Figures 2-12, 2-13, and 12-14) (Baker, 1979). The basal contact of the Catahoula Formation is delineated by the presence of coarse-grained sand and conglomerate and the underlying Jackson Sandstone in East Texas or the Frio Formation in South Texas. Specific information on the stratigraphy of the Catahoula Formation members can be found in Sellards and others (1932). The Catahoula Formation is composed of non-marine sands and clays and volcano-clastic deposits interbedded with fluviatile sediments. Surface hydrology dictated the degree of coarseness of the sediments, with larger sand grains deposited in the larger East Texas rivers and the finer sediments deposited in the smaller, lower-energy rivers of South Texas. All types and sizes of volcanic deposits are found in the Catahoula Formation, which suggests multiple source locations. The Catahoula Formation consists of approximately 60 percent volcanic material and 30 percent sandstone. The average thickness of the Catahoula Formation in the Texas Gulf Coast ranges from 200 to 600 feet in East Texas, thins to about 150 to 200 feet in Central Texas, and then thickens to about 800 to 1000 feet in South Texas. Downdip, the Catahoula Formation rapidly thickens and, at about 2,000 feet below sea level, a gulfward thickening accretionary wedge of fossiliferous marine clay appears in the upper section. This clay, called the Anahuac Formation,is overlain by the upper part of the Catahoula Formation and overlies the Frio Formation (Hosman, 1996).

## Miocene Series

The Miocene sediments comprise the Jasper aquifer and the Burkeville confining system (Baker, 1979), with the Jasper being the deepest confined water-bearing unit in the Gulf Coast aquifer system in Texas (Figures 2-12, 2-13, and 12-14). The depositional environment during the Miocene in the Gulf of Mexico Coastal Plain was essentially regressive. Intermittent sea-level reversals at various locations along the Gulf Coast produced minor transgressive cycles within the overall depositional pattern, resulting in fossiliferous marine strata ideal for correlations (Hosman, 1996). Typically, the sediments are complexly interbedded sands, silts, and clays with intermixed volcano-clastic and tuffaceous material.

The Oakville Sandstone and the Fleming Formation are composed almost entirely of terrigenous clastic sediments containing interbedded sand and clays (Baker, 1979). The Oakville Sandstone unconformably overlies the Catahoula Formation and is unconformably overlain by the Lagarto Clay of the Fleming Formation. The Oakville Sandstone generally extends in outcrop from the Brazos River basin to the Rio Grande, with the exception of areas south of Duvall County, where it is overlain by Pliocene deposits. North of the Brazos River, it is lithologically indistinguishable from the Fleming Formation but can be correlated by using vertebrate fossils (Sellards and others, 1954). The thickness of the Oakville Sandstone increases southward and gulfward to more than 500 feet in some areas (Sellards and others, 1954). Unique marine fossils found in the sediments of the Oakville Formation are used to distinguish it from adjacent geologic units.

The Fleming Formation extends throughout the Gulf Coast aquifer system in Texas and eastern Louisiana. In South Texas, the Fleming Formation is primarily composed of clays, with the

(a)

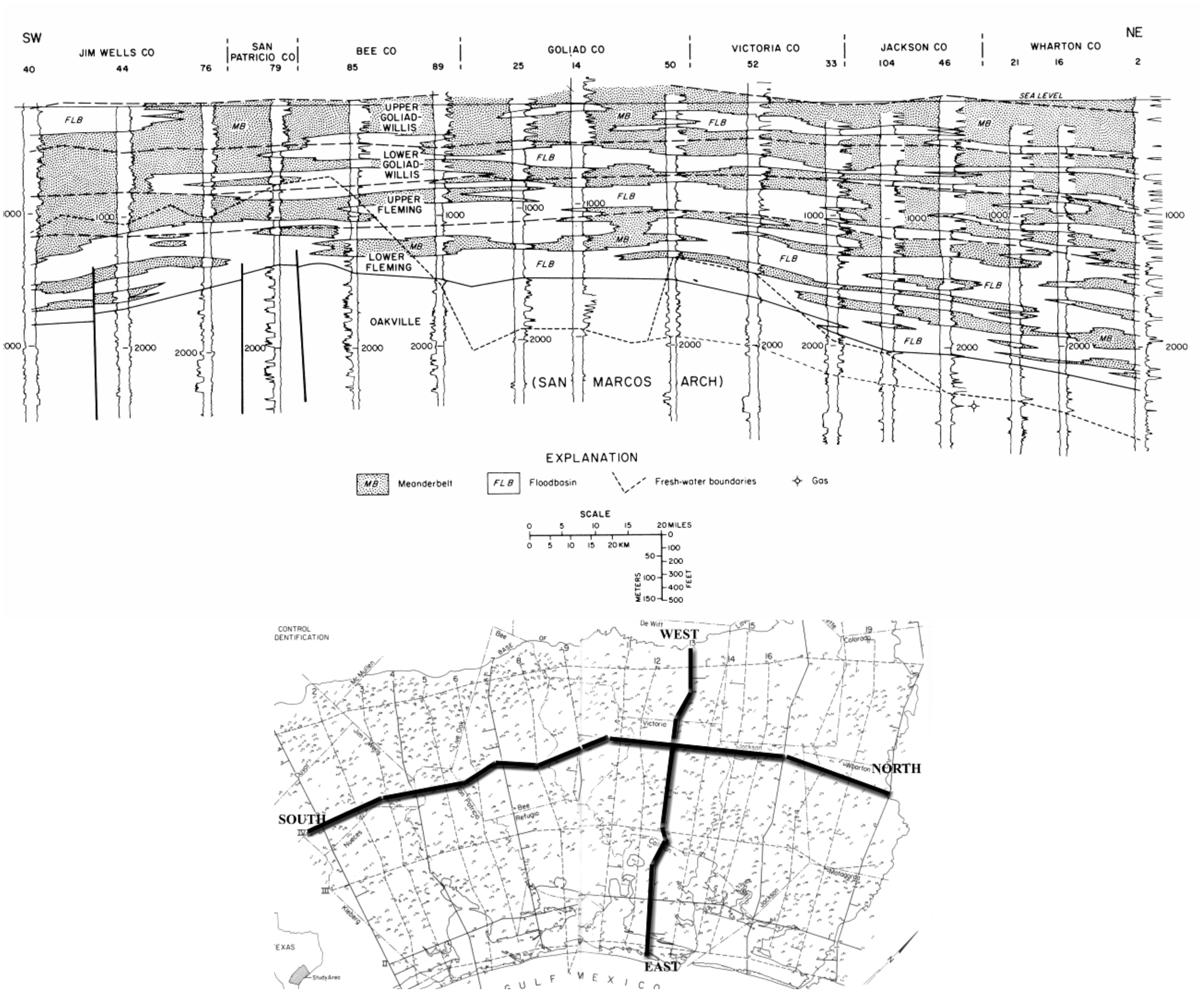

**Figure 2-13a.** **Cross-section showing thicknesses of the aquifers along strike (north-south) in the central and southern parts of the Gulf Coast. Cross-section lines are shown in inset map (from Solis, 1981). Formations thicken downdip but remain relatively uniform in thickness along strike. Note sediment thickness varies considerably across faults, suggesting fault involvement during deposition. Depositional environment for each sediment facies and fresh water contact at depth are indicated.**

percentage of sand increasing eastward towards the Sabine River. The clay beds can be many different colors and the strata can contain a thin layer of chalky sandstone as well as finely crossbedded sands in some locations (Hosman, 1996). Although the Fleming Formation is lithologically similar to the Oakville Sandstone, it is easily differentiated from the Oakville Sandstone in some places by its greater percentage of clay (Baker, 1979). While it is only about 200 feet thick in the outcrop, the Fleming Formation is thousands of feet thick downdip along the coast (Hosman, 1996). The Fleming Formation contains the Burkeville confining system and may include portions of both the Jasper aquifer at depth and the Evangeline aquifer towards up-dip areas. The Fleming Formation defines the most up-dip extent of the Miocene-aged water-bearing units in the Gulf Coast aquifer system in Texas.

(b)

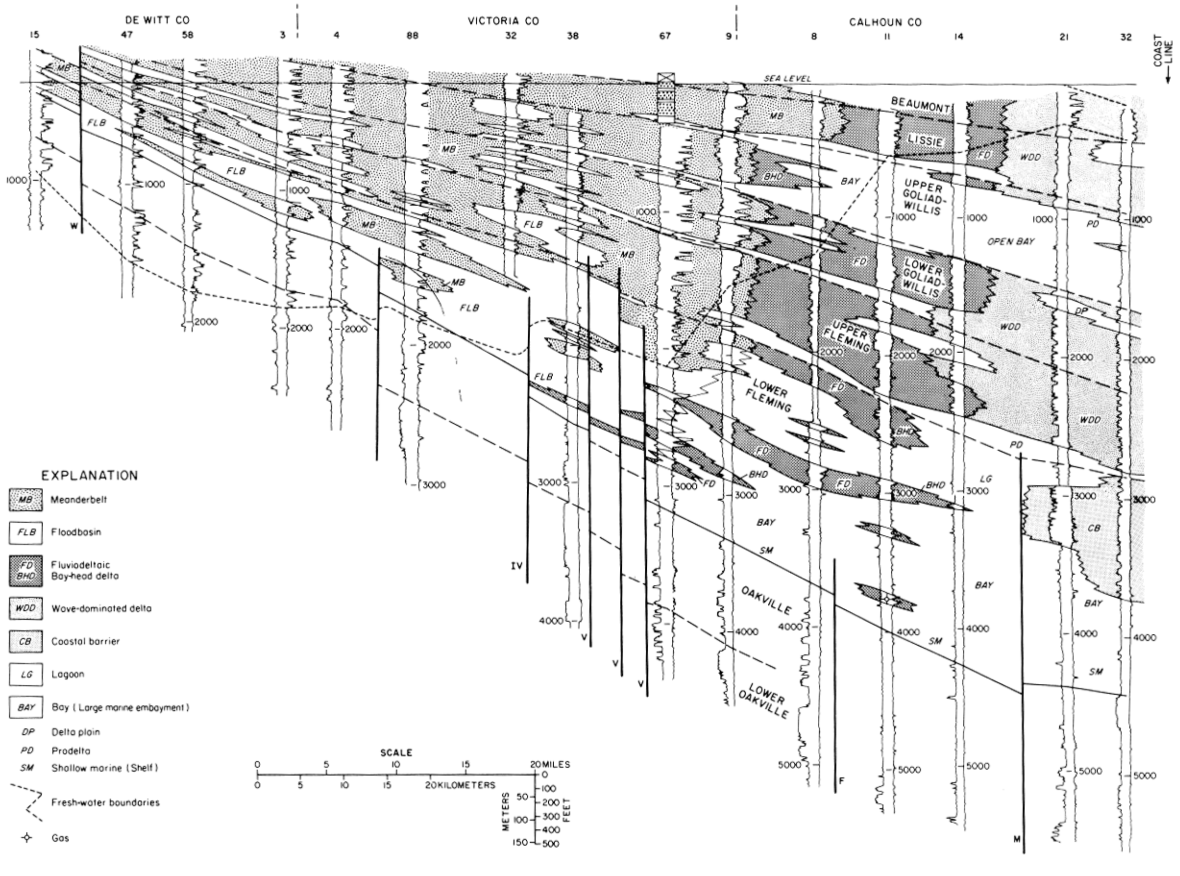

**Figure 2-13b.** **Cross-section showing thicknesses of the aquifers down-dip (east-west) in the central and southern parts of the Gulf Coast (from Solis, 1981).**

## Pliocene Series

The Pliocene-aged sediments are for the most part very similar to the Miocene-aged sediments, but may differ somewhat lithologically (Hosman, 1996). Pliocene-aged sediments can be more arenaceous and interbedded than those of the Miocene-aged sediments; the clays are less calcareous and the sands more lignitic. However, considering these differences, the Pliocene sediments are difficult to distinguish from the underlying Miocene sediments. Additionally, distinguishing between the Pliocene-aged sediments and the overlying Pleistocene-aged sediments is difficult and has resulted in similar degrees of controversy amongst geologists.

The Goliad Formation overlies the Fleming Formation and consists of coarse-grained sediments, including cobbles, clay balls, and wood fragments at the base of the formation (Hosman, 1996). The upper part of the Goliad Formation consists of finer-grained sands that are cemented with calcium carbonate called caliche (Hosman, 1996). Caliche is a surface deposit formed in semi-arid climates by the evaporation of surface waters carrying calcium bicarbonate in solution,

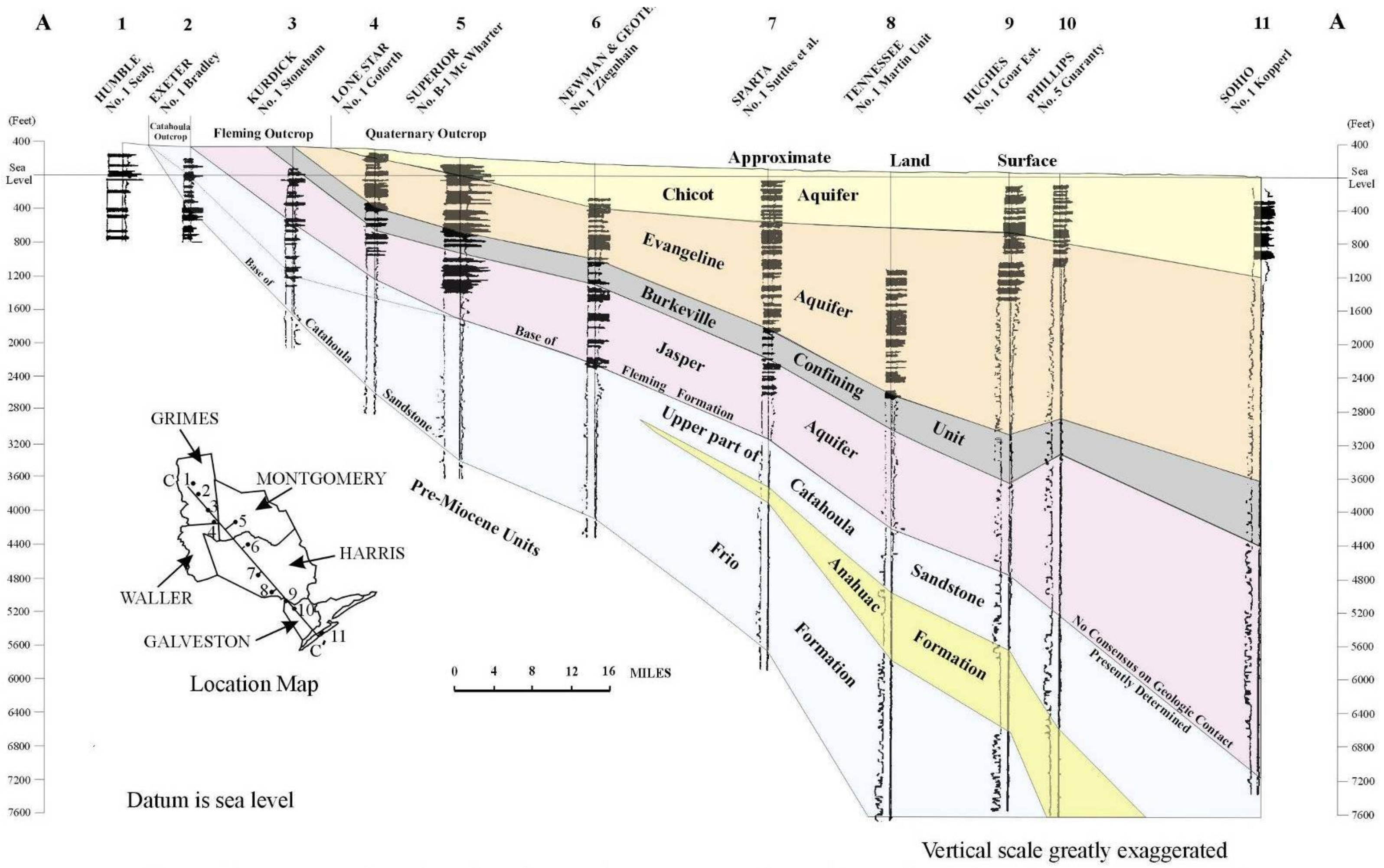

Figure 2-14. Cross-section showing thicknesses of the aquifers down-dip in the northern part of the Gulf Coast (after Baker, 1979; Kasmarek, unpublished data).

leaving the calcium carbonate precipitated in the pore spaces within the sand and gravel beds (Sellards and others, 1954). The irregular bedding, presence of gravel, and presence of some caliche in the Goliad Formation suggest a high-energy riverine depositional environment early in the Pliocene with shorter duration of semi-aridity throughout the Pliocene. The sands of the Goliad Formation are interbedded with grayish clays that are locally marly (Hosman, 1996). The sands in the Goliad Formation are typically whitish gray or pinkish grey, but in areas of increased amounts of chert it can have a salt-and-pepper appearance (Sellards and others, 1932). The Goliad Formation is entirely within the Evangeline aquifer and the upper boundary of the Evangeline aquifer probably follows closely with the top of the Goliad Formation where present (Baker, 1979).

## Pleistocene and Holocene Series

The depositional environment of the Pleistocene-aged sediments is consistent with the erosional and sedimentary cycles associated with periods of glaciation and coincident sea-level variations. Coastal terrace deposits and a fining upward sequence are typical of glacial cycling (Hosman, 1996). The Lissie Formation and Beaumont Clay are the two dominant subdivisions of the Pleistocene system. The Alta Loma Sand and the Willis Formation are locally extensive, occur over a small geographic area, and represent part of the Pleistocene system. The Holocene system consists of river alluvium and coastal deposits. The Chicot aquifer is contained entirely within the Pleistocene- and Holocene-aged sediments.

The Alta Loma and Willis sands are complexly faulted. These fluvial-deltaic sediments have been identified in the subsurface in Harris, Galveston, Chambers, and Brazoria counties (Kreitler and others, 1977). Evaluation of electric logs shows a coarsening-upward sequence, commonly indicative of delta-front facies (Kreitler and others, 1977). The Alta Loma Sand doubles in thickness from 200 feet in Harris County to 400 feet in Brazoria and Galveston counties due to fault-induced displacement of the sand.

The Willis Sand was used to describe a sequence of unfossiliferous sand and gravelly sand beds overlying the Fleming Formation in Southeast Texas (Doering, 1935; Solis, 1981). Plummer (1933) described these sediments as reddish, coarse, and gravelly sands with subordinate clays that grade into the Goliad Formation in the southwest of the Gulf Coast (Doering, 1935). In the Rio Grande region, the Willis Sand has not been identified (Weeks, 1937).

The Lissie Formation is unconformably contained between the Goliad Sand and the overlying Beaumont Clay. The Lissie Formation crops out in a band parallel to the coast and is about 30 miles wide from the Sabine River to the Rio Grande. The sediments of the Lissie Formation in the outcrop are partly continental deposits laid down on flood plains and partly as delta sands, silts, and mud at the mouth of rivers (Sellards and others, 1932). The Lissie Formation hosts flatter, gently undulating topography, and has much lower-dipping beds than the Goliad Sand. Lissie Formation sediments consist of reddish, orange, and gray fine- to coarse-grained, cross-bedded sands. Over most of Brooks and Hidalgo counties to the south, the Lissie Formation is either eroded or covered by sand dunes. Thin beds of the Lissie Formation crop out over a small area in southern Hidalgo and northern Willacy counties. The sands in the Lissie Formation are fine-grained and the formation contains relatively less conglomerates than the underlying Goliad Sand. Caliche beds often mark the base of the Lissie Formation (Price, 1934).

The Beaumont Clay is contained between the underlying Lissie Formation and overlying Holocene-aged stream deposits and wind blown sands. It outcrops from the Sabine River in the east to Kleberg County in the south. The Beaumont Clay is made up of poorly bedded, marly clay and is interbedded with lenses of sand in the north (Figure 2-15) (Sellards and others, 1932). In South Texas, the Beaumont Clay forms a thin mantle that extends eastward from Rio Grande City in Starr County to Hidalgo County (Weeks, 1937). In Starr and western Hidalgo counties, the Beaumont Clay is sandy but is composed of reddish-brown clay and some sand beds farther east (Weeks, 1937). The Beaumont Clay is contemporaneous with the Beaumont Sand, which can be generally continuous on a local scale. The Beaumont sediments were deposited largely by rivers in the form of natural levees and deltas that coalesced as river mouths shifted along the coast and, to a lesser extent, by marine and lagoonal water in the bays and embayments between stream ridges and delta banks (Sellards and others, 1932).

The Holocene-aged alluvial systems in the Texas Gulf Coast are local in scale and typically are included within the Chicot aquifer. The Brazos, Trinity, Nueces, and Rio Grande alluvial basins consist of terrace gravels, buried sand deposits, and point bar deposits with grain sizes ranging from clay to gravel. The flat-lying floodplain deposits typically consist of sand and gravel in the lower part and silt and clay in the upper part. This surficial system exhibits the largest outcrop area of all the units in the Texas Gulf Coast and provides a direct hydraulic connection in some cases between the surface water and groundwater systems.

**Figure 2-15. Photograph of a core of the Beaumont Clay at a depth of about 30 feet from a well near Houston. Whitish areas are carbonates, darker areas are organic matter, and pinkish (gray) areas are clay. Note tightness of the clay that retards any significant infiltration of recharge.**

# Conclusions

1. The Gulf of Mexico Basin was formed by downfaulting and downwarping of the Paleozoic basement rocks during the breakup of the Paleozoic megacontinent Pangaea and opening of the North Atlantic Ocean in the Late Triassic. Sediments of the Gulf Coast aquifer in Texas were deposited in the costal plains of the Gulf of Mexico Basin during the Tertiary and the Quaternary periods.
2. Structures in the Gulf Coast aquifer in Texas include the Balcones fault zone, Texas-Mexia fault zone, San Marcos arch, Sabine arch, Rio Grande embayment, numerous growth faults, and salt domes. These structural features controlled the accumulation and distribution of sediments, as supported by the observation that bedding commonly thins towards and over the arches and thickens in the embayments. Most of the growth faults and salt domes are mainly caused by gravity acting on thick sedimentary sections deposited on abnormally pressured shale or salt that sole out above the basement to produce salt-flow structures and growth faults. Salt domes and growth faults provide structural and stratigraphic traps for oil and gas fields in the prolific hydrocarbon-bearing Gulf of Mexico basin.
3. Sediments of the Gulf Coast aquifer in Texas were deposited under fluvial-deltaic to shallow-marine environments. Repeated sea-level changes and natural basin subsidence produced discontinuous beds of sand, silt, clay, and gravel. Six major sediment dispersal systems that sourced large deltas distributed sediments eroding from the Laramide Uplift along the central and southern Rockies and the Sierra Madre Oriental in northern Mexico. Geographic locations of the various fluvial-dominated systems remained relatively persistent, but the locations of the depocenters where thickest sediment accumulations occurred shifted at different times.
4. Rapid sediment loading in fluvial deltas caused overpressure zones to develop in the subsurface. Overpressure developed as connate water trapped during deposition was unable to escape during rapid burial of the sediments, giving rise to high fluid pressure.
5. The stratigraphic framework of the Gulf Coast aquifer sediments is complex and controversial, with disagreement over which units are equivalent in age and how they correlate with each other in the outcrop or the subsurface. The considerable heterogeneity of the sediments, discontinuity of the beds over short distances, a general absence of index fossils or marker beds, and an absence of diagnostic electric log signatures in the subsurface often make correlation of the lithologic units difficult.
6. The Gulf Coast aquifer in Texas consists of five hydrostratigraphic units, from oldest to youngest: the Catahoula Confining System, the Jasper aquifer, the Burkeville confining system, the Evangeline aquifer, and the Chicot aquifer. Although several stratigraphic classifications have been proposed, this classification scheme, based on detailed faunal information, lithology and electric log signatures, and hydraulic characteristics of the sediments can be successfully used for facies correlations over most of the Texas Gulf Coast. Therefore, this classification is widely accepted by the geologic community.

# References

Aronow S. and Barnes. V. E., 1968, Geologic atlas of Texas, Houston Sheet, Paul Weaver Memorial Edition.

Aronow S. and Barnes. V. E., 1975, Geologic atlas of Texas, Corpus Christi Sheet, Alva Christine Ellisor Memorial Edition.

Aronow, S., Brown, T. E., Brewton, J. L., Eargle, D. H. and Barnes, V. E., 1975, Geologic atlas of Texas, Beeville-Bay City Sheet, Alexander Deussen Memorial Edition.

Baker, R. C., and Dale, O. C., 1961, Groundwater resources of the Lower Rio Grande Valley area, Texas: Texas Board of Water Engineers, Bulletin 6014, 81 p.

Baker, E. T., Jr., 1979, Stratigraphic and hydrogeologic framework of part of the coastal plain of Texas: Texas Department of Water Resources Report 236, 43 p.

Bornhauser, M., 1958, Gulf Coast tectonics: American Association of Petroleum Geologists Bulletin, v. 42, p. 339–370.

Brewton, J. L., Owen, F., Aronow , S., and Barnes, V. E., 1976a, Geologic atlas of Texas, McAllen-Brownsville Sheet, Arthur Carleton Trowbridge Memorial Edition.

Brewton, J. L., Owens, F., Aronow, S., and Barnes, V. E., 1976b, Geologic atlas of Texas, Laredo Sheet, Julia Gardner Memorial Edition.

Bruce, C. H., 1973, Pressured shale and related sedimentary deformation—Mechanism for development of regional contemporaneous faults: American Association of Petroleum Geologists Bulletin, v. 57, p. 878–886.

Bryant, W. R., Lugo, J., Cordova, C., and Salvador, A., 1991, Physiography and bathymetry, *in* Salvador, A., editor, The Gulf of Mexico Basin: Boulder, Colorado, Geological Society of America, The Geology of North America, v. J., p. 13–30.

Bureau of Economic Geology, 1976, Geologic atlas of Texas, McAllen-Brownsville sheet: The University of Texas at Austin, Bureau of Economic Geology.

Byerly, G. R., 1991, Igneous activity, *in* Salvador, A., editor, The Gulf of Mexico Basin: Boulder, Colorado, Geological Society of America, The Geology of North America, v. J., p. 91–108.

Chowdhury, A. H., Bogichi, R. and Hopkins, J., this volume, Hydrochemistry, salinity distribution, and trace constituents—Implications for salinity sources, geochemical evolution, and flow system characterization: Proceedings of the Gulf Coast Aquifer Conference, Corpus Christi, Texas Water Development Board Report 365, p 81–128.

Chowdhury, A. H., and Mace, R. E., 2003, A groundwater availability model for the Gulf Coast aquifer in the Lower Rio Grande Valley, Texas—Numerical simulations through 2050: Texas Water Development Board, unpublished report, 171 p.

Cloos, E., 1962, Experimental analysis of Gulf Coast fracture patterns: American Association of Petroleum Geologists Bulletin, v. 52, p. 420–444.

Doering, J., 1935, Post-Fleming surface formations of coastal Southeast Texas and South Louisiana: Bulletin American Association of Petroleum Geologists, v. 19, p. 651–688.

Dutton, A. R. and Richter, B. C., 1990, Regional hydrogeology of the gulf coast aquifer in Matagorda and Wharton counties, Texas – Development of a numerical flow model to estimate the impact of water management strategies: Report prepared for the Lower Colorado River Authority under contract (88-89) 0910, Bureau of Economic Geology, University of Texas at Austin, 118 p.

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

Fisher, W. L., and McGowen, J. H., 1967, Depositional systems in the Wilcox Group of Texas and their relationship to the occurrence of oil and gas: Gulf Coast Association of Geological Societies Transactions, v. 17, p. 105–125.

Gabrysch, R. K., 1984, Case history no. 9.12. The Houston-Galveston region, Texas, USA, *in* Poland, J. F., editor, Guidebook to studies of land subsidence due to groundwater withdrawal: UNESCO Studies and Reports in Hydrology 20, p. 253–262.

Galloway, W. E., 1968, Depositional systems of the Lower Wilcox Group, North-Central Gulf Coast Basin: Gulf Coast Association of Geological Societies Transactions, v. 18, p. 275–289.

Galloway, W. E., 1977, Catahoula Formation of the Texas Coastal Plain, depositional systems, composition, structural development, groundwater flow, history and uranium distribution: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigation no. 87, 59 p.

Galloway, W. E., 1989, Genetic sequences in basin analysis II—Application to northwest Gulf of Mexico Cenozoic basin: Bulletin American Association of Petroleum Geologists, v. 73, p. 143–154.

Galloway, W. E., 2005, Gulf of Mexico Basin depositional record of Cenozoic North American drainage basin evolution: International Association of Sedimentologists Special Publication 35, p. 409–423.

Galloway, W. E., Ganey-Curry, P. E., Li, X., and Buffler, R., 2000, Cenozoic depositional history of the Gulf of Mexico Basin: American Association of Petroleum Geologists Bulletin, v. 84, p. 1743–1774.

Grubb, H. F., 1998, Summary of hydrology of the regional aquifer systems, Gulf Coastal plain, South-Central United States—Regional aquifer system analysis—Gulf Coastal Plain: U.S. Geological Survey Professional paper 1416-A, p. 61 p.

Guevara-Sanchez, E. H., 1974, Pleistocene facies in the subsurface of the southeast Texas Coastal Plain: The University of Texas at Austin, unpublished Ph.D. dissertation, 133 p.

Halbouty, M. T., and Halbouty, J. J., 1982, Relationships between East Texas Field region and the Sabine uplift in Texas: American Association of Petroleum Geologists Bulletin, v. 66, p. 1042–1054.

Hamlin, S., this volume, Salt domes in the Gulf Coast aquifer: Texas Water Development Board Report 365, p. 217–230.

Hosman, R. L., 1996, Regional stratigraphy and subsurface geology of Cenozoic deposits, Gulf Coastal Plain, South-Central United States—Regional aquifer system analysis—Gulf Coastal Plain: U.S. Geological Survey Professional Paper 1416-G, 35 p.

Hosman, R. L. and Weiss, J. S., 1991, Geohydrologic units of the Mississippi Embayment and Texas Coastal Uplands Aquifer Systems, South-Central United States—Regional aquifer system analysis—Gulf Coastal Plain: U.S. Geological Survey Professional Paper 1416-B, 19 p.

Jackson, M. P. A., and Galloway, W. E., 1984, Structural and depositional styles of Gulf Coast Tertiary continental margins—Applications to hydrocarbon exploration: Continuing Education Course Notes Number 25, American Association of Petroleum Geologists, 225 p.

Jones, P. H., 1969, Hydrology of Neogene deposits in the northern Gulf of Mexico basin: Louisiana State University, Louisiana Water Resources Research Institute Bulletin GT-2, 105 p.

Jorgensen, D. G., 1975, Analog-model studies of groundwater hydrology in the Houston district, Texas: Texas Water Development Board Report 190, 84 p.

Kasmarek, M. C., and Robinson, J. L., 2004, Hydrogeology and simulation of groundwater flow and land-surface subsidence in the northern part of the Gulf Coast aquifer system: U.S. Geological Survey, Scientific Investigations Report 2004-5102, 111 p.

Kreitler, C. W., Guevera, E., Granata, G., and McKalips, D., 1977, Hydrogeology of the Gulf Coast aquifers, Houston-Galveston area, Texas: Transactions—Gulf Coast Association of Geological Societies, v. XXVII, p. 72–89.

Leach, W. G., 1994, Distribution of hydrocarbons in abnormal pressure in South Louisiana, USA, *in* Fertl, W. H., Chapman, R. E., and Holtz, R. F., editors, Studies in Abnormal Pressures: Elsevier.

Leach, W. G., and Fertl, W. H., 1990, The relationship of formation pressure and temperature to lithology and hydrocarbon distribution in Tertiary sandstones: Tranactions of the International Well Logging Symposium, section E, Beijing, China.

McCoy, T. W., 1990, Evaluation of groundwater resources in the Lower Rio Grande Valley, Texas: Texas Water Development Report 316, 47 p.

Morton, R. A., Han, J. H., and Posey, J. S., 1983, Variations in chemical composition of Tertiary formation waters, Texas Gulf Coast, *in* Morton, R. A., and others, editors, Consolidation of geologic studies of geopressured geothermal resources in Texas, 1982 Annual Report: The University of Texas at Austin, Bureau of Economic Geology, report prepared for the U.S. Department of Energy under contract no. DE-AC08-79ET27111, p. 63–135.

Mukherji, T., Dutta, N., Prasad, M., and Dvorkin, J., 2002, Seismic detection and estimation of overpressures, Part I: the Rock Physics Basics, Canadian Society of Exploration Geophysicists Recorder, p. 36–57.

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

Nelson, T. H., 1991, Salt tectonics and listric-normal faulting, *in* Salvador, A., editor, The Gulf of Mexico basin: Geological Society of America, The Geology of North America, v. J., p. 73–89.

Plummer, F. B., 1933, Cenozoic Systems in Texas: Geology of Texas, vol. 1, Stratigraphy, University of Texas Bulletin 3232, p. 519–818.

Price, W. A., 1934, Lissie Formation and Beaumont Clay in South Texas: Bulletin of the American Association of Petroleum Geologists, v.18, no. 7, p.948–959.

Proctor, C. V., Brown, T. E., Waechter, N. B., Aronow, S., and Barnes, V. E., 1974, Geologic atlas of Texas, Seguin Sheet, Donald Clinton Barton Memorial Edition.

Quarles, M., 1952, Salt-ridge hypothesis of Texas Gulf Coast type of faulting: American Association of Petroleum Geologists Bulletin, v. 37, p. 489–508.

Rose, N. A., 1943a, Groundwater and relationship of geology to its occurrence in Houston district, Texas: Bulletin of the American Association of Petroleum Geologists, v. 27, p. 1081–1101.

Rose, N. A., 1943b, Progress report on the groundwater resources of the Texas City area, Texas: U.S. Geological Survey Open-file report, 45 p.

Salvador, A., 1991, Introduction, *in* Salvador, A., editor, The Gulf of Mexico Basin: Geological Society of America, The Geology of North America, v. J., p. 1–12.

Sellards, E. H., Adkins, W. S., and Plummer, F. B., 1932, The Geology of Texas, Volume I, Stratigraphy: The University of Texas at Austin, Bureau of Economic Geology, 1007 p.

Shah, S. D., and Lanning-Rush, J., 2005, Principal faults in the Houston, Texas, Metropolitan Area: U.S. Geological Survey Scientific Investigations Map 2874, 4 p.

Shelby, C. A., Pieper, M. K., Aronow, S., and Barnes, V. E., 1968, Geologic atlas of Texas, Beaumont Sheet, Harold Norman Fisk Memorial Edition.

Solis, R. F., 1981, Upper Tertiary and Quaternary depositional systems, central Coastal Plain, Texas—Regional geology of the coastal aquifer and potential liquid-waste repositories: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations 108, 89 p.

Spearing, D., 1991, Roadside geology of Texas: Mountain Press Publishing Company, Missoula, Montana, 418 p.

Strom, E. W., Houston, N. A., and Garcia, C. A., 2003a, Selected hydrologic data sets for the Chicot aquifer: U.S. Geological Survey, Open File Report.03-297, 1 CD-ROM.

Strom, E. W., Houston, N. A., and Garcia, C. A., 2003b, Selected hydrologic data sets for the Evangeline aquifer: U.S. Geological Survey, Open File Report 03-298, 1 CD-ROM.

Strom, E. W., Houston, N. A., and Garcia, C. A., 2003c, Selected hydrologic data sets for the Jasper aquifer: U. S. Geological Survey, Open File Report 03-299, 1 CD-ROM.

Verbeek, E. R., Ratzlaff, K. W., and Clanton, U. S., 1979, Faults in parts of north-central and western Houston metropolitan area, Texas: U.S. Geological Survey Miscellaneous Field Studies Map MF-1136, 1 sheet.

Vogler, H. A., and Robinson, B. A., 1987, Exploration for deep geopressured gas, Corsair trend, offshore Texas: American Association of Petroleum Geologists Bulletin, v. 71, p. 777–787.

Weeks, A. W., 1937, Miocene, Pliocene and Pleistocene formations in Rio Grande region, Starr and Hidalgo counties, Texas: Bulletin of the American Association of Petroleum Geologists, v. 21, no. 4, p. 491–499.

Williamson, A. K. and Grubb, H. F., 2001, Groundwater flow in the Gulf Coast aquifer systems, Regional aquifer system analysis—Gulf Coastal Plain, U.S. Geological Survey Professional Paper 1416-F, 173 p.

Wood, L. A., Gabrysch, R. K., and Marvin, R., 1963, Reconnaissance investigation of the groundwater resources of the Gulf Coast region, Texas: Texas Water Commission, Bulletin 6305, 114 p.

Xue, L., and Galloway, W. E., 1993, Sequence stratigraphy and depositional framework of the Paleocene Lower Wilcox strata, Northwest Gulf of Mexico Basin: Gulf Coast Association of Geological Societies Transactions v. 43, p. 453–464.