GEOHYDROLOGIC UNITS OF THE COASTAL LOWLANDS AQUIFER SYSTEM SOUTH-CENTRAL UNITED STATES

REGIONAL AQUIFER-SYSTEM ANALYSIS

Geohydrologic Units of the Coastal Lowlands Aquifer System, South-Central United States

By JONATHAN S. WEISS

REGIONAL AQUIFER-SYSTEM ANALYSIS—GULF COASTAL PLAIN

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 following a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.

Dallas L. Peck
Director

CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

TABLES

METRIC CONVERSION FACTORS

For readers who prefer to use metric units, conversion factors for terms used in this report are listed below:

Multiply inch-pound units	*By*	*To obtain metric units*
Foot (ft)	0.3048	meter (m)
mile (mi)	1.6093	kilometer (km)
square mile (mi^2)	2.5900	square kilometer (km^2)
pound per square inch (lb/in^2)	6.8948	kilopascal (kPa)

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

GEOHYDROLOGIC UNITS OF THE COASTAL LOWLANDS AQUIFER SYSTEM, SOUTH-CENTRAL UNITED STATES

By JONATHAN S. WEISS

ABSTRACT

The coastal lowlands aquifer system is one of the three regional aquifer systems studied as part of the Gulf Coast Regional Aquifer-System Analysis (RASA). The coastal lowlands aquifer system underlies about 160,000 square miles of the coastal areas of Texas, Louisiana, Mississippi, Alabama, and westernmost Florida, and nearby offshore areas; the aquifer system is composed of sediments of Oligocene age and younger. The sediments consist predominantly of interbedded sand, silt, and clay with minor amounts of lignite and limestone. The average thickness of the sediments is about 6,000 feet, with a maximum thickness of more than 18,000 feet occurring offshore from southern Louisiana.

The base of the coastal lowlands aquifer system is the top of the Vicksburg-Jackson confining unit, which is a massive clay that represents the last major transgression of the sea. A zone of abnormally high fluid pressure (geopressured zone) is present above the top of the Vicksburg-Jackson confining unit onshore in a narrow band along the coast of Texas and Louisiana and on the Continental Shelf. Where the geopressured zone is present, it is considered to be the base of the coastal lowlands aquifer system.

The sediments in the coastal lowlands aquifer system are divided into five permeable zones and two confining units. The permeable zones are not separated by intervening, regionally mappable confining units in about 64 percent of the study area. In much of the area boundaries between permeable zones were extended, as a constant proportion of the total aquifer system thickness, from areas with hydraulic-head data to areas without such data.

Average sand percentage of the permeable zones ranges from about 40 percent to more than 60 percent. However, the areal distribution of sand is variable within and among permeable zones. A lobate pattern of greater sand percentages is typical of the permeable zones, and all zones except one have at least one area with sand percentage greater than 80 percent.

Data that are useful for quantitative analysis of regional ground-water flow in the coastal lowlands aquifer system are presented in map format. Included for each of the five permeable zones are maps of altitude of the top, thickness, sand percentage, and aggregate thickness of sand. Included for each of the two confining units are maps showing altitude of the top and thickness of the unit.

INTRODUCTION

A major objective of the Regional Aquifer-System Analysis (RASA) program is to provide an understanding of ground-water flow systems on a regional scale (Bennett, 1979). Natural hydrologic boundaries, rather than political boundaries, have been used to determine the various areas to be studied. The Gulf Coast RASA study encompasses about 230,000 mi^2 of onshore area in parts of Alabama, Arkansas, Florida, Illinois, Kentucky, Mississippi, Missouri, Tennessee, Texas, and all of Louisiana. The study area also includes 60,000 mi^2 of offshore area on the Continental Shelf where the permeable strata extend beyond the coastline beneath the Gulf of Mexico. The Gulf Coast RASA study and its relation to adjacent RASA studies is shown in figure 1.

This report describes the geohydrologic framework of the coastal lowlands aquifer system, one of the three regional aquifer systems delineated in the Gulf Coast RASA study area (fig. 2 and Grubb, 1984). The coastal lowlands aquifer system is composed predominantly of Oligocene and younger sediments, whereas the Mississippi embayment aquifer system and the Texas coastal uplands aquifer system are composed predominantly of Eocene sediments. Each of the three aquifer systems is composed of thousands of feet of deposits, which contain numerous aquifers, permeable zones, and confining units. Some of these geohydrologic units are regionally extensive, whereas others are of local importance.

The geohydrologic framework of two aquifer systems, the Mississippi embayment and the Texas coastal uplands, is described in chapter B of this Professional Paper (Hosman and Weiss, 1991). The

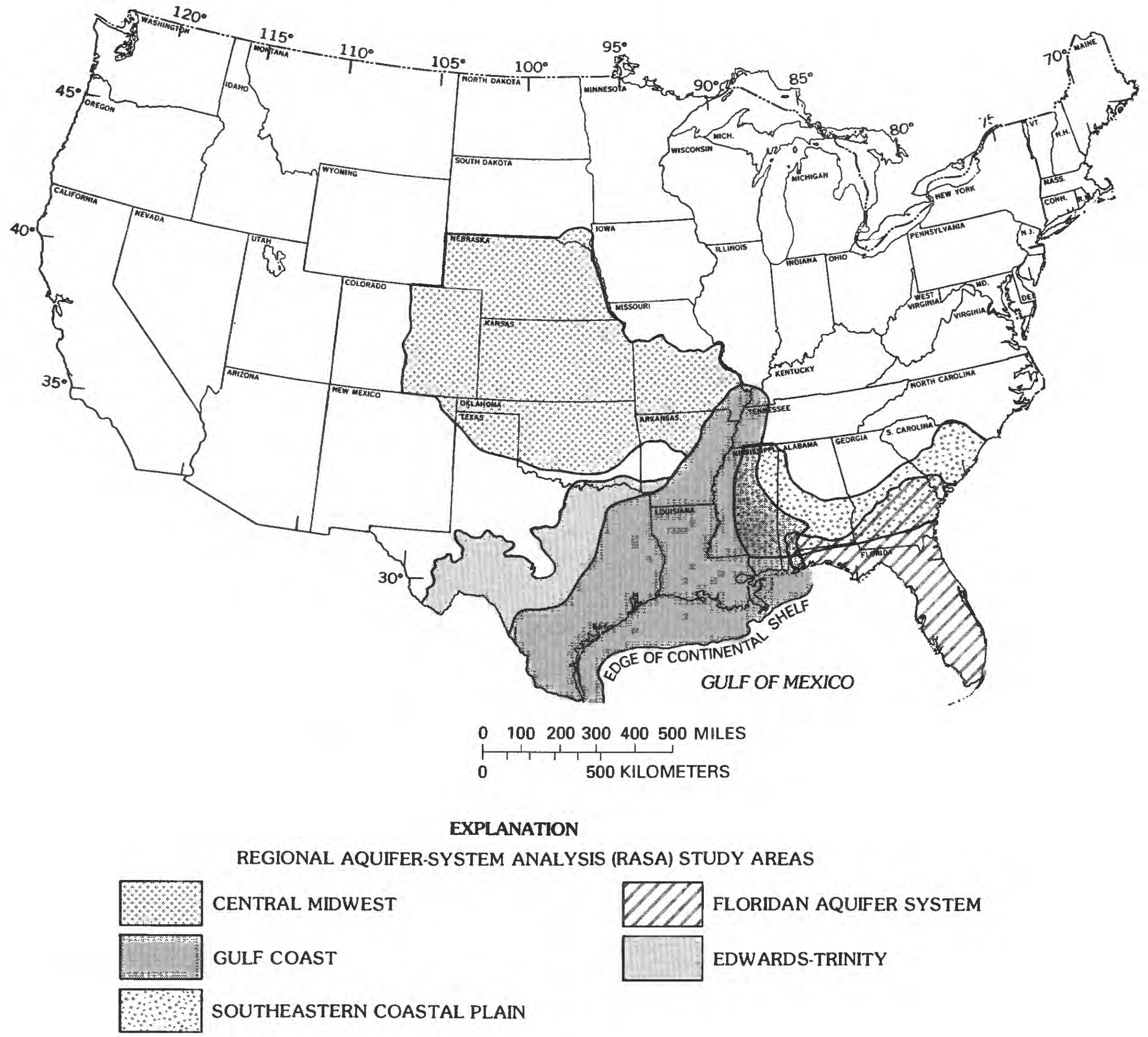

FIGURE 1.—Relation of the Gulf Coast Regional Aquifer-System Analysis study to adjacent Regional Aquifer-System Analysis studies.

coastal lowlands aquifer system (this report) overlies the other two systems and is separated from them by a regionally extensive major confining unit, the Vicksburg-Jackson confining unit.

The coastal lowlands aquifer system underlies about 160,000 mi^2 in parts of Alabama, Florida, Louisiana, Mississippi, and Texas from the Rio Grande on the west to the western part of Florida on the east. The gulfward boundary of the aquifer system is the edge of the Continental Shelf (defined as about the 600-ft bathymetric contour). The updip boundary is the contact between the massive clay of the undivided Jackson and Vicksburg Groups and the younger sandy deposits of Oligocene or Miocene age.

PURPOSE AND SCOPE

The purpose of this report is to present maps that are useful for quantitative analysis of regional ground-water flow in the coastal lowlands aquifer system. The mapped divisions of the aquifer system are referred to as geohydrologic units, consisting of permeable zones and confining units. The primary difference between the permeable zones and the confining units is that the horizontal component of flow is important in the permeable zones but is not a significant factor in the confining units.

Geologic processes that affected and controlled the development of the geohydrologic framework are described to provide an understanding of some of the

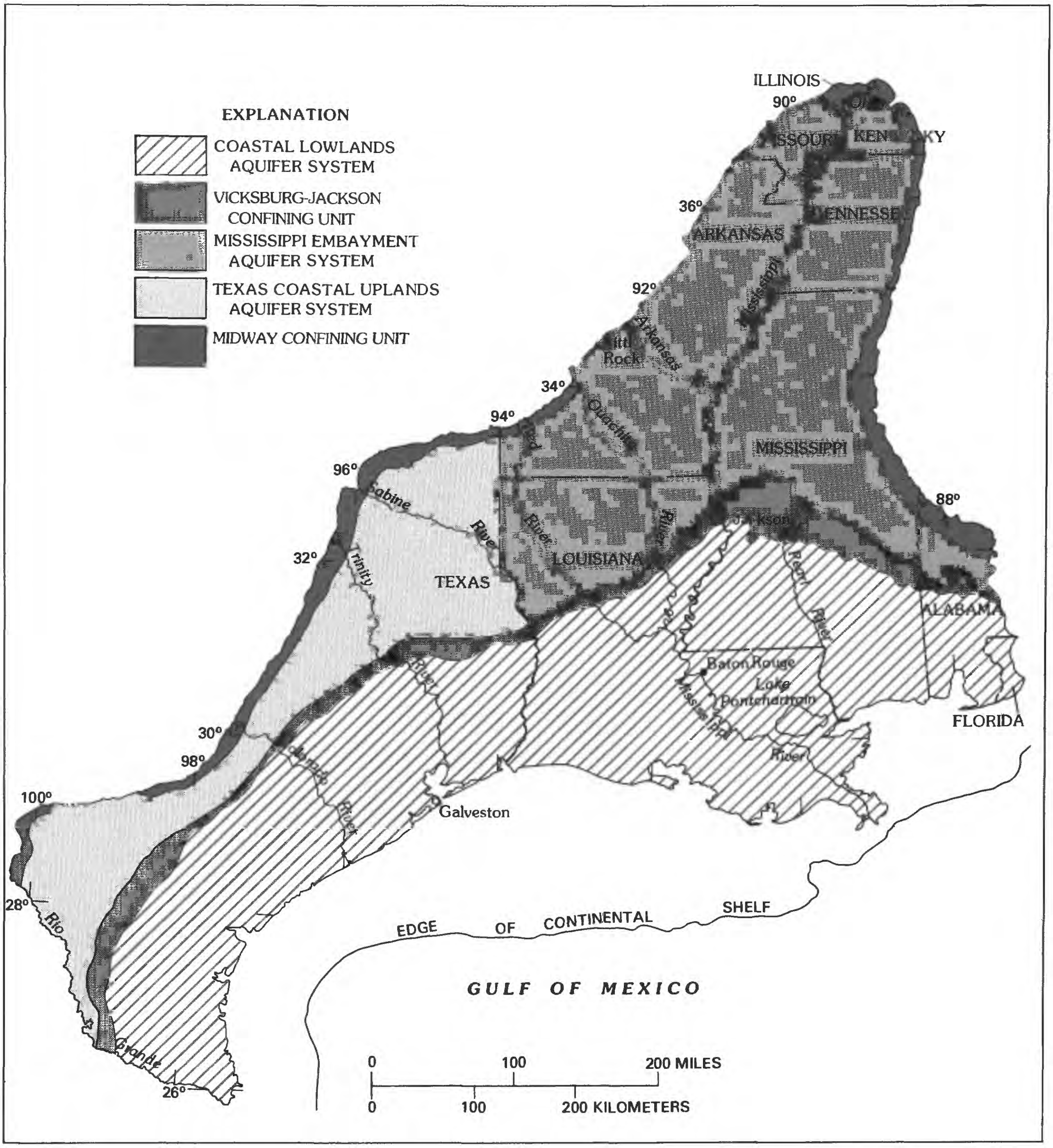

FIGURE 2.—Generalized outcrop of major aquifer systems and confining units in the Gulf Coast Regional Aquifer-System Analysis study area.

basic controls on the occurrence and movement of ground water in the study area. Depositional environments, influenced by major tectonic features, produced the vast sedimentary complex that is the coastal lowlands aquifer system, largely a heterogeneous assortment of clastic sediments that thickens gulfward to many thousands of feet. The sheer bulk of the coastal lowlands aquifer system required that it be divided vertically into permeable zones and confining units to enable meaningful quantitative studies. The boundaries between permeable zones were defined by criteria established during this study. Because the geohydrologic framework deviates from the classic concept of geohydrologic units—that is, aquifers separated by confining units—the boundaries between the permeable zones could be placed differently depending on the level of detail needed for division of the system.

APPROACH

A geohydrologic framework for the Gulf Coast RASA was constructed from analysis of approximately 1,000 borehole geophysical logs (Wilson and Hosman, 1988) selected as those most representative of the regional characteristics in the study area. About 550 logs are for wells in the area underlain by the coastal lowlands aquifer system (pl. 1), with almost 100 of these logs from offshore locations. Values determined from the borehole geophysical logs and used in this report include depth to top and thickness of identifiable stratigraphic or geohydrologic units, or both, depth to tops and thickness of individual sand beds (coarse-grained sediments) greater than 20 ft thick, and the aggregate thickness of sand beds less than 20 ft thick.

Maps of the various characteristics of the coastal lowlands aquifer system were initially made by using Surface II, a computer contouring system (Sampson, 1978), which performed a linear interpolation of the randomly spaced data to create estimates at uniformly spaced 5-mi intervals. Geologic and hydrologic judgment were used to refine the maps where necessary. Maps of the tops of geohydrologic units were produced by subtracting the interpolated thickness of the overlying unit from the altitude of the top of that unit. The intent of the mapping was to depict regional trends.

The map depicting the base of the coastal lowlands aquifer system was produced directly from the bore-hole geophysical-log data; information from this map was the basis for delineating the base of the aquifer system on the geohydrologic sections presented in this report (pl. 1 shows the traces of the sections; table 1 identifies the wells used to construct the sections). The map of the total aquifer-system thickness was determined by plotting the difference between the base of the aquifer system and either land surface or the sea floor. Logs of wells that did not reach the base of the aquifer system were not used for mapping the aquifer-system thickness.

Most of the units delineated in this study are truncated downdip by the presence of a zone of abnormally high fluid pressure commonly called geopressure. Abnormally high fluid pressures are defined as pressures that exceed the hydrostatic pressure of a column of water containing 80,000 mg/L (milligrams per liter) of dissolved solids (Dickinson, 1953). An equivalent pressure of approximately 0.465 lb/in^2 per foot of water height would be exerted by this column (Jones, 1969). The cause of the geopressured zones is likely a combination of factors. During compaction of sediments, fluids are expelled along paths of least resistance. An increase in the resistance to flow, particularly as caused by compaction of clay, restricts the expulsion of fluids; this results in an increase in pressure. The excess pressure in such geopressured zones slows the rate of further compaction, and the sediments in these zones remain undercompacted. Faults that occur contemporaneously with deposition, known as growth faults, are considered a principal cause of geopressured zones where they truncate and thus effectively isolate sand beds, which in turn restricts fluid expulsion. Because completely impermeable barriers to flow are rare or nonexistent in sedimentary basins, pressure in geopressured zones eventually will decrease to near hydrostatic pressure given enough time.

The top of the geopressured zone in the study area was identified on bore-hole geophysical logs as the top of the logged interval in which the drilling-mud weight was substantially increased to resist high formation pressure. The top of the geopressured zone was further refined where increased resistivity within that logged interval could be recognized; this increase indicates the occurrence of undercompacted sediments. A map of the top of the geopressured zone by Wallace and others (1981) was used for supplementary information. Further discussions on the occurrence of geopressure can be found in Jones (1969), Jones and Wallace (1974), and Fertl (1976).

The southernmost limit of the coastal lowlands aquifer system is placed at the edge of the Continental Shelf (fig. 2). Only the uppermost units are truncated at this point, as lower units are terminated further updip by geopressure. Extrapolations into Mexico in the southern end of the study area are not shown on the maps; instead, all maps truncate at the international boundary along the Rio Grande.

Previous investigators have made various attempts to divide the Oligocene and younger sediments of the study area into geologic or geohydrologic units locally, but none of the divisions extends regionally. A review of the work of previous investigators is presented below. A brief discussion of the geohydrologic framework is followed by a general discussion of aquifer systems and geohydrologic units which includes criteria used in this study to divide the coastal lowlands aquifer system into various geohydrologic units. Finally, each of the geohydrologic units is discussed in detail.

PREVIOUS INVESTIGATIONS

Various divisions of the Oligocene and younger sediments of the Gulf of Mexico sedimentary basin by previous investigators are listed in table 2. Early investigators defined several geologic units for the Miocene and younger sediments of the Gulf Coastal Plain, primarily based on surface exposures. However, Jones and others (1956) determined that stratigraphy inferred from the area of outcrop in southwestern Louisiana provided no usable basis for differentiation in the subsurface. Jones and others (1956) assigned hydrologic-unit names to stratigraphic units and traced them into the subsurface where possible. The name "Chicot aquifer" was assigned to the predominantly sand and gravel sediments of Pleistocene age, which includes in descending order the Prairie, Montgomery, Bentley, and Williana Formations. The name "Evangeline aquifer" was assigned to the Foley Formation of Pliocene age, which consists predominantly of sand and clay. Facies changes occurring downdip and along the strike make differentiation of Pleistocene from pre-Pleistocene sediments difficult and the top of the Evangeline aquifer hard to identify. Jones and others (1956) described the relatively poor continuity of individual beds in the Evangeline aquifer but suggested that the beds are interconnected. The base of the Evangeline was not described by Jones and others (1956) partly due to few data and partly because it was outside the scope of their investigation.

Jones and others (1956) stated that serious difficulties remained in correlating units of southwestern Louisiana with neighboring southeastern Texas. However, Turcan and others (1966) traced the Chicot and Evangeline aquifers across the State line into Texas. They also named two additional units, the Burkeville confining unit and the Jasper aquifer, which they traced back to Louisiana. These four hydrologic units were traced to Houston, Texas, although it was recognized by Turcan and others (1966) that the geologic names assigned to the sediments in southeastern Texas conflicted in part with those used for similar sediments in the Houston area.

Earlier studies in the Houston area by Lang and others (1950) recognized layers of massive clay interfingering with and grading laterally and vertically into thin sand zones, with sand and gravel grading likewise into the clay zones. They determined that thinner beds pinched out within a few hundred feet and that even persistent clay zones could not be traced much beyond the Houston area. In addition, similar to the studies made in southwestern Louisiana, Lang and others (1950) recognized that some of the subsurface beds in the Houston area are apparently not equivalent to identifiable beds at the surface. For the purpose of their analysis, Lang and others (1950) divided several thousand feet of sediments in the Houston area into seven zones, primarily based on electrical logs. The zones were not named but were numbered from 1 to 7 in ascending order. The zones were based on deep marker beds, thus reflecting the regional dip rather than being simple horizontal divisions. The futility in attempting any regional correlations of these zones is demonstrated by the fact that the zones could not be identified in part of the Houston area (Lang and others, 1950).

Wood and Gabrysch (1965) combined several of the zones of Lang and others into a "heavily pumped layer" at Houston, Texas. This layer is several thousand feet thick. The top of the layer was defined as the base of the Alta Loma Sand of Rose (1943), where present, or the base of a confining layer composed of alternating beds of sand and clay. The confining layer was referred to as the Beaumont Clay where it is predominantly clay, and the Lissie Formation where it is predominantly sand. The base of the "heavily pumped layer" is the top of zone 2 of Lang and others (1950). This horizon does not represent a formation boundary or an effective hydraulic boundary but was arbitrarily chosen to represent the base of the "heavily pumped layer" in the Houston area (Wood and Gabrysch, 1965).

Jorgensen's (1975) description of water-bearing units in the Houston area used aquifer terminology suggested by Turcan and others (1966). At Houston, in ascending order, the Chicot aquifer is composed of the Willis Sand, Bentley Formation, Montgomery Formation, Beaumont Clay, and Quaternary alluvium. In some areas near Houston, Jorgensen separated the Chicot into an upper and lower unit, following Wesselman (1971). The primary distinction between the two units was the altitude of their potentiometric surfaces. Where the upper unit was not recognizable, he referred to the Chicot aquifer as undifferentiated. The Chicot aquifer included all deposits from land surface to the top of the Evangeline aquifer. In some places, Jorgensen separated the Chicot aquifer from the underlying Evangeline aquifer at the base of the Alta Loma Sand of Rose (1943), a heavily pumped massive sand (not to be confused with the "heavily pumped layer" of Wood and Gabrysch, 1965). However, Jorgensen preferred not to use the name "Alta Loma Sand"; this unit is not everywhere identifiable, and its stratigraphic relations are not clear. The primary criteria he used in separating the Chicot aquifer from the Evangeline aquifer were differences in hydraulic conductivity. This difference is not always obvious.

TABLE 1.—*Wells used in construction of geohydrologic sections, coastal lowlands aquifer system*

[Location of wells shown on pl. 1]

County, parish, or offshore area	Company name	Well name	Well No.
	Alabama		
Washington	Humble Oil & Refining Co.	No. 1, J. R. Williams	41
	Louisiana		
Acadia	Humble Oil & Refining Co.	No. 1, North Crowley Gas Unit 23	34
Calcasieu	The California Co.	No. 1, C. O. Noble, et al. 3	64
Evangeline	Shell Oil Co.	No. 1, Forman	31
	Magnolia Petroleum Corp.	No. 1, Brunet Granger	32
Grant	Seaboard Oil Co.	No. 1, Joe Shorter	28
	H. L. Hunt	No. F–1, Goodpine	27
Iberville	Humble Oil & Refining Co.	No. 2, Jeanerette Lumber & Shingle Co.	66
Jefferson Davis	C. H. Lawrence & Texas Eastern Transmission Corp.	No. 1, Nelson H. Thomas	65
Plaquemines	The California Co.	No. 1, State Lease 2122	49
	David S. Thayer	No. 3, J. E. Fasterling	50
Rapides	Caroline Hunt Sands	No. 1, C. Keller	29
	Moran Oil Co.	No. 1, Meeker	30
St. Bernard	Shell Oil Co.	No. 1, State Lease 1280	47
	Shell Oil Co.	No. 1, State Lease 4281	68
St. Charles	The California Co.	No. 3, U.S.A.	67
St. Landry	Tidewater Assoc. Oil Co.	No. 1, Woody Guillory	33
Vermillion	Shell Oil Co.	No. 1, State Lease 3636	36
	Texaco, Inc.	No. 1, C. L. Huntsberry	35
Offshore	Texaco, Inc.	No. 4, Mound Point, State Lease 340	37
	Kerr-McGee Corp.	No. 1, OCS–G–2303	38
	Atlantic Richfield Co.	No. 1, OCS–G–3775	39
	Chevron U.S.A., Inc.	No. 4, OCS–G–2323	40
	Continental Oil Co.	No. A–1, State Lease 971	51
	Chevron Oil Co.	No. 1, OCS–G–2171	52
	Phillips Petroleum Co.	No. 1, State Lease 2191	48
	Mississippi		
George	Hassie Hunt Trust	No. 1, H. C. McLain	44
	The Ohio Oil Co.	No. 1, L. N. Dantzler	45
Green	Shell Oil Co.	No. 1, Lucas et al. (cat 11)	42
	Getty Oil Co.	No. 1, M. L. Davis Estate 25–10	43
Jackson	Humble Oil & Refining Co.	No. B–1, L. N. Dantzler Lumber Co.	46

particularly on a regional scale. The Evangeline aquifer is composed of the Goliad Sand and the uppermost part of the Fleming Formation. Below the Evangeline aquifer, Jorgensen recognized the Burkeville confining layer as equivalent to zone 2 of Lang and others (1950). These same divisions were used for digital-modeling studies of the ground-water system in the Houston area, Texas, by Meyer and Carr (1979) and Carr and others (1985).

Other workers outside of the Houston area had varying degrees of difficulty in recognizing these units. Wilson (1967) did not recognize the Chicot aquifer in Austin and Waller Counties, Texas, and instead included in the Evangeline aquifer all the sediments between the alluvium of the Brazos River and the Burkeville confining layer. He agreed with the stratigraphic position of the Burkeville confining layer within the Fleming Formation, but extended the underlying Jasper aquifer deeper into the Catahoula Sandstone. A later study by Sandeen (1968) in nearby San Jacinto County, Texas, recognized the Chicot aquifer above the Evangeline aquifer. Popkin (1971) also recognized the Chicot aquifer above the Evangeline aquifer in Montgomery County, Texas, and in addition divided the Jasper aquifer into two units. Wesselman (1971) divided the Chicot aquifer in Chambers and Jefferson Counties, Texas, into two units based on a clay bed that separates the sand

TABLE 1.—*Wells used in construction of geohydrologic sections, coastal lowlands aquifer system*—Continued

County, parish, or offshore area	Company name	Well name	Well No.
	Texas		
Aransas	Union Producing Co.	No. 10, Tatton	57
Bee	Atlantic Richfield	No. 1, C. O. Dougherty	10
	Shell Oil Co.	No. 1, Alvin L. O'Neal	9
	Pure Oil Co.	No. 1, O'Brien-Harkins "B"	11
Brazoria	Tide Water Associated Oil Co.	No. 1, Ramsey Prison Farm	61
	Phillips Petroleum	No. 1, State Tract 51000	23
	Humble Oil and Refining Co.	No. 1, C. W. Massey	21
Brazos	The Texas Co.	No. 1, Orlando	17
Calhoun	Coastal States Gas Producing Co. & Royal Resources	No. 1, Duncan	58
Cameron	Chevron Oil Co.	No. 1, Jose A. Rodriguez	4
	Texaco, Inc.	No. 1, C. A. Johnson	3
Chambers	Belco Petroleum Corp.	No. 1, Crawford 159	62
Galveston	Cities Service Petroleum Co.	No. B-2, Stewart	22
Grimes	Placid Oil Co.	No. 1, Robert Foster	18
Harris	Pan American Petroleum Corp.	No. 1, Houston Unit	20
	Texaco, Inc.	No. 1, M. M. Mergele	19
Hidalgo	Coastal States Gas Producing Co. and Greenbrier, Ltd.	No. 1, Severo C. Castillo	2
	Shell Oil Co.	No. 1, W. H. Drawe	53
Kenedy	Humble Oil & Refining Co.	No. 1, H. F. McGill	54
Kleberg	Lone Star Producing Co.	No. 1, Bessie H. Muil	55
Live Oak	Standard Oil Company of Texas	No. 1, Mrs. Clay West, Burns	128
Matagorda	Sun Oil Co.	No. 1, Clara Junek	59
	Sun Oil Co.	No. D-1, Braman	60
Nueces	Socony Mobil Oil Co., Inc., David Geiser, and Molirey Oil Co.	No. 1, E. R. Russell	56
	Cities Services	No. 1, State Tract 773	14
	Kirkpatrick Oil & Gas Co. and Natol Petroleum	No. 1, Annie Polacek Regmund	127
Orange	John W. Mecom	No. 2, E. W. Brown	63
San Patricio	Transcontinental Production Co.	No. 2, Ewing	12
	Tenneco Oil Co.	No. 1, M. C. Campbell	13
Starr	Austral & Tidewater Oil Co.	No. 1, Jennie V. Sanchez	1
Willacy	Pan American Petro. Corp.	No. 1, Marie C. N. De Armendaiz	5
Wilson	O. G. McClain	No. 1, S. V. Houston	8
Offshore	Atlantic Richfield Co.	No. 1, State Tract 12275	6
	Superior Oil Co.	No. 1, OCS–G–2982	7
	Union Oil Co. of Calif.	No. L, State Tract 775–L (No. 57748)	15
	Superior Oil Co.	No. 1, OCS–G–3047	16
	Shell Oil Co.	No. 1, Fed. Blk 288 (OCS 0709)	24
	Amoco Oil Corp.	No. 3, OCS–G–2364	25
	Mobil Oil Corp.	No. 3, OCS–G–2393, Blk. A–573	26

intervals. Water-level differences were noted in wells completed in the two units. These sands merge in some places, making separation into two units extremely difficult if not impossible, and in other places one of the sands may be absent. Sandeen and Wesselman (1973) also were able to divide the Chicot aquifer into two units in Brazoria County, Texas. Earlier studies by Wesselman (1965) in Orange County, Texas, simply divided all the Miocene and younger sediments into the lower, middle, and upper aquifers. These were divisions of Baker's (1964) Gulf Coast aquifer, which combined all the formations into one unit, based on similarit in litholo-, anc th

features that could easily be traced into the subsurface. Later work by Baker (1979), however, resulted in the tracing of the Chicot, Evangeline, and Jasper aquifers and the Burkeville confining layer across Texas, from the Louisiana-Texas State line to the Rio Grande.

Baker's (1979) correlations identified one Chicot unit, restricted to sediments of Pleistocene age, as was done in Louisiana by Jones and others (1956). Recognizing the difficulty in everywhere identifying the base of the Pleistocene, however, Baker (1979) acknowledged the uncertainty in the boundary between the Chicot aquifer and the underlying Evan-

Table 2.—*Geologic and geohydrologic units defined in this and previous reports,*

Erathem	System	Series	Jones and others (1956)		Turcan and others (1966)				Lang and others (1950)		Wood and Gabrysch (1965)		Jorgensen (1975)		Wilson (1967)		Sandeen (1968)		Popkin (1971)	
			Southwestern Louisiana		Southwestern Louisiana		Southeastern Texas		Houston area, Texas		Houston area, Texas		Houston area, Texas		Austin and Waller Counties, Texas		San Jacinto County Texas		Montgomery County Texas	
Cenozoic	Quaternary	Holocene, Pleistocene	Prairie Formation Montgomery Formation Bentley Formation Williana Formation	Chicot aquifer	Prairie Formation Montgomery Formation Bentley Formation Williana Formation	Chicot aquifer	Beaumont Clay Alta Loma Sand of Rose (1943) Lissie Formation	Chicot aquifer	Beaumont Clay Alta Loma Sand of Rose (1943) Lissie Formation	Zone 7 6	Beaumont Clay Alta Loma Sand of Rose (1943) Lissie Formation	Confining layer	Alluvium Beaumont Clay Mont-gomery Formation Bentley Formation Willis Sand	Upper Chicot aquifer Lower Chicot aquifer	Brazos River alluvium Beaumont Clay Montgomery Formation Bentley Formation	Evangeline aquifer	Alluvium Beaumont Clay Lissie Formation	Chicot aquifer	Alluvium Beaumont Clay Montgomery Formation Bentley Formation	Chicot aquifer
	Tertiary	Pliocene	Foley Formation	Evangeline aquifer	Foley Formation	Evangeline aquifer	Willis Sand (Pliocene?) Goliad Sand	Chicot aquifer Evangeline aquifer	Willis Sand (Pliocene?) Goliad Sand	5	Willis Sand (Pliocene?) Goliad Sand	"Heavily pumped layer"	Goliad Sand	Evangeline aquifer	Willis Sand (Pliocene?) Goliad Sand	Evangeline aquifer	Willis Sand (Pliocene?) Goliad Sand	Chicot aquifer Evangeline aquifer	Willis Sand (Pliocene?) Goliad Sand	Chicot aquifer Evangeline aquifer
		Miocene	Fleming Formation of Fisk (1940)	Evangeline aquifer ?	Fleming Formation of Fisk (1940) Lena Member of Fisk (1940)	Evangeline aquifer Burkeville aquiclude Jasper aquifer Unnamed aquiclude	Lagarto Clay Oakville Sandstone	Evangeline aquifer Burkeville aquiclude Jasper aquifer	Lagarto Clay Oakville Sandstone	4 3 2 1	Lagarto Clay Oakville Sandstone	"Heavily pumped layer" Zone 2	Fleming Formation	Evangeline aquifer Burkeville confining layer Upper Jasper aquifer Lower Jasper aquifer	Fleming Formation	Evangeline aquifer Burkeville aquiclude Jasper aquifer	Fleming Formation	Evangeline aquifer Burkeville aquiclude Jasper aquifer	Fleming Formation	Evangeline aquifer Burkeville aquiclude Upper Jasper aquifer Lower Jasper aquifer
		? Oligocene	Catahoula Sandstone				Catahoula Sandstone		Catahoula Sandstone Anahuac Wedge		Catahoula Sandstone				Catahoula Sandstone	Jasper aquifer	Catahoula Sandstone		Catahoula Sandstone	
		Eocene													Undifferentiated		Jackson Group		Jackson Group	

coastal lowlands aquifer system, south-central United States

WESSELMAN (1971) / SANDEEN AND WESSELMAN (1973)		WESSELMAN (1965)		BAKER (1964)		BAKER (1979)		MEYER AND TURCAN (1955)	ROLLO (1960)	HARDER (1960)		NYMAN AND FAYARD (1978)	ROLLO (1966)	THIS REPORT
Chambers and Jefferson Counties, Texas / Brazoria County, Texas		Orange County, Texas		Hardin County, Texas		Coastal Plain, Texas		Baton Rouge area, Louisiana	Baton Rouge area, Louisiana	Calcasieu Parish, Louisiana		Tangipahoa and St. Tammany Parishes, Louisiana	New Orleans area, Louisiana	Gulf Coast
Alluvium Beaumont Clay Montgomery Formation Bentley Formation	Upper Chicot aquifer Lower Chicot aquifer	Alluvium Beaumont Clay Alta Loma Sand of Rose (1943) Lissie Formation	"Upper" aquifer "Middle" aquifer	Alluvium Beaumont Clay Lissie Formation	Gulf Coast aquifer	Alluvium Beaumont Clay Montgomery Formation Bentley Formation Willis Sand	Chicot aquifer	"400-foot"sand "600-foot"sand "800-foot"sand "1,000-foot"sand "1,200-foot"sand "1,500-foot"sand "1,700-foot"sand	"400-foot" sand "600-foot" sand	Alluvium Prairie Formation Montgomery Formation Bentley Formation Williana Formation	"200-foot" sand "500-foot" sand "700-foot" sand	Shallow aquifer Upper Ponchatoula aquifer	Shallow aquifer "200-foot" sand "500-foot" sand "700-foot" sand "1,200-foot" sand	Permeable zone A (Holocene-upper Pleistocene deposits)
Willis Sand (Pliocene?) Goliad Sand	Evangeline aquifer	Willis Sand (Pliocene?) Goliad Sand	"Lower" aquifer	Willis Sand (Pliocene?) Goliad Sand		Goliad Sand	Evangeline aquifer	(No sands assigned to Pliocene)	"800-foot" sand "1,000-foot" sand "1,200-foot" sand "1,500-foot" sand "1,700-foot" sand	Foley Formation	Evangeline aquifer	Lower Ponchatoula aquifer Big Branch aquifer Kentwood aquifer Albita aquifer Covington aquifer Slidell aquifer		Permeable zone B (lower Pleistocene-upper Pliocene deposits)
Fleming Formation	Burkeville aquiclude	Lagarto Clay Oakville Sandstone		Lagarto Clay Oakville Sandstone		Lagarto Clay Oakville Sandstone	Burkeville confining system Jasper aquifer	"2,000-foot" sand "2,400-foot" sand "2,800-foot" sand	"2,000-foot" sand "2,400-foot" sand "2,800-foot" sand	Fleming Formation		Tchefuncta aquifer Hammond aquifer Amite aquifer Ramsay aquifer Franklinton aquifer		Permeable zone C (lower Pliocene-upper Miocene deposits) Zone D confining unit Permeable zone D (middle Miocene deposits)
				Catahoula Sandstone		Catahoula Sandstone Anahuac Formation "Frio" Formation Frio Clay / Vicksburg Group ? Jackson Group	Catahoula confining system (restricted)			Catahoula Formation				Zone E confining unit Permeable zone E (lower Miocene-upper Oligocene deposits) Vicksburg-Jackson confining unit

defined by Jones and others (1956), was restricted to sediments of Pliocene age. Baker's (1979) correlations were determined independently from time-stratigraphic concepts, and in places the basal part of the Evangeline aquifer includes some sediments of Miocene age. Likewise, the underlying Burkeville confining unit transgresses geologic-time boundaries because it represents only the uppermost Miocene in some places and extends downward into the middle Miocene in other places.

The Jasper aquifer, originally named by Turcan and others (1966) for the town of Jasper, in Jasper County, Texas, underlies the Burkeville confining layer. Although originally identified in Texas, the base of the Jasper aquifer was placed at the top of a clay identified as the Lena Member of Fisk (1940) of the Fleming Formation in Louisiana. Whitfield (1975) mapped the Jasper aquifer in southwestern Louisiana according to the described boundaries, although he acknowledged that in many places the contacts were indistinct. Choosing to not recognize the Lena Member in Texas, Baker (1979) mapped the Jasper aquifer as a rock-stratigraphic unit. In parts of Texas, including at the type locality of the Jasper aquifer, Baker (1979) included the upper part of the Catahoula Sandstone in the Jasper aquifer. As this was only done in parts of Texas, the Jasper aquifer in Texas, as defined by Baker (1979), has an irregular geometry. Baker (1979) attributed the discrepancy at the Texas-Louisiana border to different interpretations of the surface geology at the State line and believed that as long as this discrepancy exists, subsurface correlations will continue to differ.

The Catahoula Sandstone underlies the Jasper aquifer. Although sandy in outcrop in Texas, the clay content of the Catahoula Sandstone increases as the section thickens rapidly downdip. Baker (1979) refers to this clayey unit as the Catahoula confining system (restricted). The parenthetic "restricted" is used because in some areas the hydrologic unit has different boundaries from those of the stratigraphic unit. The Catahoula Sandstone has been further differentiated downdip into three stratigraphic units. The differentiation can largely be attributed to the presence of the Anahuac Formation (Ellisor, 1944), a thick marine clay facies, in the approximate middle of this section. However, the Anahuac Formation is not easily traced everywhere, because it is in places interbedded with deltaic sands, resulting in a poorly defined updip margin (Galloway and others, 1982). Baker (1979) referred to the section above the Anahuac Formation as the upper part of the Catahoula confining system and the section below the Anahuac Formation as the "Frio" Formation, as used in the subsurface by many petroleum geologists. This usage of the term "Frio" in quotation marks distinguishes this sandy formation from the updip occurrence of the Frio Clay, which historically has not been considered correlative. However, Galloway and others (1982) correlated the Frio Clay in part with the Catahoula Sandstone and "Frio" Formations of the deep subsurface and in part with the Vicksburg Formation of Oligocene age.

The Catahoula Sandstone was included in the description of southwestern Louisiana geology by Jones and others (1956) where it marks the base of the Miocene. It is recognized at land surface but has a marine character downdip. Jones and others (1956) made no mention of the Anahuac or "Frio" Formation. However, Bebout and Gutierrez (1983) recognized the Anahuac and "Frio" Formations in southwestern Louisiana based largely on paleontological evidence, as the character of the two formations is similar on geophysical logs. They referred to the section immediately overlying the Anahuac Formation as lower Miocene, rather than Catahoula Sandstone, and suggested an Oligocene age for the Anahuac and "Frio" Formations. Baker (1979) suggested that the Anahuac and "Frio" Formations of Texas may be of Oligocene age. If these units are downdip equivalents of the Catahoula Sandstone in Texas, as Baker (1979) implied, then the Catahoula Sandstone transgresses geologic-time boundaries, as it is predominantly Miocene in age. Bebout and Gutierrez (1983) grouped the Jackson Group and Vicksburg Formation as one unit where they underlie the "Frio" Formation in Louisiana.

Bebout and Gutierrez (1983) also traced the Anahuac and "Frio" Formations across southeastern Louisiana. Differentiation and correlation of shallower sediments were apparently less successful, as they only recognized relative time-stratigraphic position, such as lower Miocene, upper Miocene, and so forth. This section is composed of many thin beds of limited areal extent. Abundant ground-water supplies in southeastern Louisiana are developed from several horizons, particularly at Baton Rouge and New Orleans. Meyer and Turcan (1955) described 10 different aquifers for Baton Rouge. Although clay units were recognized between the aquifers, no formal confining units were identified. The aquifers were named according to their depth at the industrial district of Baton Rouge where ground-water pumpage was substantial. This convention was used with the understanding that the depth to each aquifer does not remain constant throughout the area, because the exact depth depends on both the surface altitude and on the regional dip of the strata. Accordingly, the "400-foot" sand at New Orleans, as defined by Rollo (1966), and the "400-foot" sand at Baton Rouge are two different aquifers because strata at New Orleans are downdip from those at Baton Rouge. However, divisions based on depth were satisfactory for local studies (Torak and Whiteman, 1982) where the primary interest is in the response of individual beds to pumping stresses.

Meyer and Turcan (1955) identified all the sediments above the Miocene in the Baton Rouge area as Pleistocene in age because of the lithologic differences from Pliocene sediments in southwestern Louisiana. By their definition, the base of the Pleistocene is at the base of the "1,700-foot" sand. However, Rollo (1960) correlated the base of the Pleistocene in southwestern Louisiana with the base of the "600-foot" sand in the Baton Rouge area and described all sediments between this contact and the base of the "1,700-foot" sand as being of Pliocene age. If this section is equivalent to the Evangeline aquifer, as suggested by Martin and Whiteman (1985b), the base of the Evangeline aquifer agrees with that described by Turcan and others (1966) for southeastern Texas but does not correlate with their base in southwestern Louisiana nor does it correlate with the base of the Evangeline aquifer described by most other workers elsewhere in Texas. However, the age of the base of the section thought to be equivalent to the Evangeline aquifer in the Baton Rouge area remains uncertain. Rollo's (1960) correlation of the "400-foot" and "600-foot" sands at Baton Rouge as Pleistocene in age was accepted by Martin and Whiteman (1985a) as equivalent to the sands of the Chicot aquifer in southwestern Louisiana.

Other workers have used various methods for delineating aquifers in Louisiana. Harder (1960) divided the Chicot aquifer in Calcasieu Parish into the "200-foot," "500-foot," and "700-foot" sands. Nyman and Fayard (1978) traced and assigned names to the various sand units in Tangipahoa and St. Tammany Parishes in southeastern Louisiana, although they acknowledged the discontinuity of the deposits with abrupt lithologic changes in short distances. Rogers and Calandro (1965) and Rogers (1981) described the ground-water resources in Vernon Parish and the Alexandria area using rock-stratigraphic terminology without dividing the section into hydrologic units.

The problems in attempting to use divisions of Oligocene and younger sediments made by previous investigators for quantitative analysis of the coastal lowlands aquifer system can be summarized as follows:

1. Regional geohydrologic units have been identified in some areas. The upper and lower boundaries of the units are indefinite, however, and correlations across large distances are difficult, if not impossible.
2. Individual beds have been mapped in detail, as in southeastern Louisiana, but also are difficult to trace laterally for large distances. Naming geohydrologic units based on their depth of occurrence at a particular location can be misleading, because a unit can be at a drastically different depth at other locations.
3. The variety of names used by other investigations prevents the use of any of these names for a convenient and consistent naming of geohydrologic units across the entire study area.
4. Time-stratigraphic units are difficult to trace, although paleontological evidence has allowed time correlations across some areas. Time-stratigraphic units may have little relation to geohydrologic units, which are important for ground-water investigations.
5. The nature of the sedimentation complicates correlation of rock-stratigraphic units across the entire study area. Many correlations are speculative and are subject to varying interpretations. Correlations across State lines, particularly at the Texas-Louisiana State line, are inconsistent.

GEOHYDROLOGIC SETTING

The sediments that make up the geohydrologic units of the coastal lowlands aquifer system were deposited in the Gulf Coast geosyncline, and in the Rio Grande, Houston, and Terrebonne embayments (pl. 2) during the late Oligocene, Miocene, and Pliocene epochs of the Tertiary Period and during the Pleistocene and Holocene epochs of the Quaternary Period. The depositional environments of these strata, shifting between fluvial, deltaic, and shallow marine conditions, controlled the lithologies and the resulting hydrologic characteristics of the strata. In general, the more sandy fluvial and nearshore beach deposits are permeable but are complexly interbedded with less permeable clayey palustrine and lagoonal deposits. Few clay layers or other fine-grained deposits are continuous or extensive enough to form regional confining units. Thus the sediments make up an aquifer system in which vertical resistance to ground-water flow is due primarily to the presence of clay layers or other fine-grained deposits of local extent.

Deposition during the Tertiary Period was affected by regional crustal subsidence, inflow of sediment from beyond the Gulf Coastal Plain, and eustatic sea-level change (Galloway, 1989). The principal structural feature in the area is the Gulf Coast geosyncline (Bornhauser, 1958), which resulted from subsidence of the Earth's crust prior to the Tertiary Period. Differential loading at the mouths of large stream systems carrying sediment from the interior of the continent (Wilhelm and Ewing, 1972) caused more localized subsidence and the development of subordinate structures such as embayments and arches. Gravity flow of buried sediments near the margins of thick deltaic deposits resulted in growth faulting and typically thickening of the strata in a gulfward direction as deltas grew outward toward the center of the basin. As sea levels rose, the landward migration of marine environments resulted in the deposition of massive marine clays. As sea levels fell, seaward migration of deltaic and nearshore environments resulted in the deposition of interbedded sand, silt, and clay; deltas then grew gulfward over previously deposited sediments.

Marine clays of the undifferentiated Jackson (Eocene) and Vicksburg (Oligocene) Groups form an extensive regional confining unit. The confining unit separates the coastal lowlands aquifer system from the underlying Texas coastal uplands and Mississippi embayment aquifer systems. This confining unit is the basal unit for most of the coastal lowlands aquifer system onshore. In most of the coastal counties of Texas and Louisiana and the adjacent Continental Shelf, aquifers, permeable zones, and confining units of the coastal lowlands aquifer system are truncated by the geopressured zone.

Strata of late Oligocene age, which overlies the Vicksburg Group, contains sand beds in the updip deltaic facies and a massive clay in the deep-basin marine facies downdip. The sand beds are hydraulically interconnected with overlying deposits of early Miocene age in updip areas and form the lowermost, regionally significant permeable zone. The deep-basin clay facies combines with a deep-basin marine clay of early Miocene age downdip forming a regional confining unit which does not crop out in the study area.

Overlying strata of the Miocene Series contain sand beds of varying thickness complexly interbedded with silt and clay. Locally sand beds may be massive; however, most of the deposits are composed of interbedded sand, silt, and clay of deltaic, palustrine, lacustrine, lagoonal, and fluvial origin. These sediments make up regionally significant permeable zones. One deep-basin marine clay facies occurs downdip and forms a regional confining unit in parts of coastal Texas and offshore Louisiana. The marine clay facies does not crop out in the study area and is the uppermost regional confining unit in the area.

Deposits of the Pliocene Series overlie Miocene deposits and are typically composed of interbedded sand, silt, and clay. Pliocene sediments are very similar to those of the Miocene Series but are generally more sandy and thinly interbedded. Nonetheless, Pliocene deposits are difficult to distinguish from underlying Miocene deposits; the precise contact is commonly based on faunal criteria and not on lithology. Pliocene deposits are hydraulically connected with the underlying Miocene deposits in a typical aquifer-system relationship above the uppermost marine clay facies of the Miocene Series. Pliocene strata are generally covered by thin Pleistocene terrace deposits except for an extensive Pliocene outcrop band in south Texas.

Terrace (Pleistocene) and alluvial (Holocene) deposits overlie Pliocene strata in a wide band across the Coastal Plain adjacent to the Gulf of Mexico. These fluvial deposits are commonly coarse grained sand and gravel at the base and typically grade finer upward to silt and clay. These sediments are typically permeable and are hydraulically connected to both surface streams and underlying permeable sediments of the Pliocene Series.

The Gulf Coast geosyncline, the predominant structural feature in the area (pl. 2), affected deposition during the Tertiary Period. The sediments generally crop out in parallel bands and dip toward the axis of the geosyncline that parallels the coastline. Subordinate structures such as embayments, arches, and flexures resulting from subsidence affected the thickness and dip of strata. Beds are generally thinner over arches and thicker in the embayments with large increases in thickness across regional flexures. The Terrebonne embayment in southeastern Louisiana, and the Houston and Rio Grande embayments in Texas are significant embayments in the area. Important uplifts are the San Marcos arch in Texas and the Wiggins anticline and Hancock arch in southeastern Mississippi (pl. 2).

Numerous growth faults (faults developing during depositional episodes) occur in the area, forming regional growth-fault zones (Bruce, 1972) that are typically parallel to the coastline. These fault zones do not seem to be a major control on the regional movement of ground water but may be significant locally. These faults are important relative to the movement of hydrocarbons, especially in the deeper parts of the system.

Three salt-dome basins occur across the area from southern Texas to southern Mississippi (pl. 2, and Halbouty, 1979). The salt basin in southern Texas is south and west of the San Marcos arch and is the smallest. The largest salt basin lies to the east of the San Marcos arch and extends across most of southeastern Texas, southern Louisiana, and the adjacent Continental Shelf. The third salt basin extends from west-central Mississippi in a southeasterly direction across Mississippi and a short distance into southwestern Alabama. Salt domes in these basins penetrate most or all overlying strata at any given location, although only a few penetrate sediments of late Oligocene age in the southern Texas and Mississippi salt basins. The source of salt in the domes is generally considered to be the deeply buried Louann Salt of Jurassic age (Andrews, 1960), which was mobilized during subsequent depositional episodes. The most obvious structural effects of dome penetration are complex faulting. However, the domes are typically small, 1 to 3 mi in diameter, and thus do not have a significant effect on regional structure. The effects of salt domes on regional ground-water flow are likewise localized, except for the possible effects of salt dissolution and the resulting highly mineralized water deep in the aquifer system.

AQUIFER SYSTEMS AND GEOHYDROLOGIC UNITS

Aquifers and permeable zones in the study area have been grouped into three major aquifer systems for purposes of this study (Grubb, 1984): (1) the coastal lowlands aquifer system, (2) the Mississippi embayment aquifer system, and (3) the Texas coastal uplands aquifer system. The coastal lowlands aquifer system includes all Miocene through Holocene sediments that occur above the geopressured zone from the Rio Grande on the southwest to the westernmost county of Florida on the southeast. Also included in the coastal lowlands aquifer system are the uppermost Oligocene deposits above the massive marine clays of the Vicksburg Group. The marine clays of the Vicksburg Group combined with the underlying Jackson Group, form the Vicksburg-Jackson confining unit, which is generally several hundred feet thick (Hosman, 1988, Hosman and Weiss, 1991). Underlying Paleocene through Oligocene (Vicksburg Formation only) deposits are the Mississippi embayment aquifer system and the laterally equivalent Texas coastal uplands aquifer system, which are described in a separate report (Hosman and Weiss, 1991).

The Mississippi embayment aquifer system is 1,000 ft thick or more in most of its area of occurrence (fig. 2). The aquifer system thins to extinction at the inland margins of the study area and thickens southward toward the Gulf Coast geosyncline and toward the axis of the Mississippi embayment. It is thickest, about 5,000 ft, in southeastern Mississippi. This aquifer system then thins gulfward as sand facies disappear. The Texas coastal uplands aquifer system (fig. 2), which is contiguous with the Mississippi embayment aquifer system, is thickest (about 7,000 ft) southwest of the Sabine uplift, in the Houston embayment. The aquifer system thins somewhat over the San Marcos arch, then thickens again to about 7,000 ft southwest of the arch (Hosman and Weiss, 1991).

In order to do a quantitative ground-water flow analysis, it was necessary to divide the coastal lowlands aquifer system, which is more than 15,000 ft thick along much of coastal Louisiana (pl. 6), into discrete geohydrologic units. Because the system does not contain regionally identifiable confining units throughout much of the area, division of the aquifer system into a customary succession of alternating aquifers and confining units is not possible. Therefore, a set of criteria, at least partly arbitrary, was established for dividing the aquifer system into discrete permeable zones. These criteria, from Weiss and Williamson's (1985) description of methods for division of thick sedimentary units for ground-water flow analysis are summarized as follows:

1. Identification of areally extensive sediments of minimal permeability as regional confining units.
2. Identification of large hydraulic conductivity contrasts between adjacent permeable sediments not separated by identifiable confining units.
3. Identification of variations in hydraulic head between permeable zones with depth.
4. Extension of the units determined by criterion 1, 2, or 3 as a constant proportion of total thickness throughout areas where criteria 1, 2, or 3 could not be applied. Minor adjustments to thickness values were made at locations of bore-hole geophysical logs.

Because of the similarity of the sediments noted earlier, criterion 2 (above) was not important for dividing the coastal lowlands aquifer system into geohydrologic units. Thus the aquifer system was divided into five permeable zones and two confining units on the basis of criteria 1, 3, and 4. The permeable zones were designated alphabetically beginning with the uppermost zone, and the confining units were named for the immediately underlying permeable zone (the zone they confine). The divisions (geohydrologic units) in descending order are as follows:

- Permeable zone A (Holocene–upper Pleistocene deposits)
- Permeable zone B (lower Pleistocene–upper Pliocene deposits)
- Permeable zone C (lower Pliocene–upper Miocene deposits)
- Zone D confining unit
- Permeable zone D (middle Miocene deposits)
- Zone E confining unit
- Permeable zone E (lower Miocene–upper Oligocene deposits).

Zone D confining unit and zone E confining unit were delineated by the application of criterion 1—namely, the identification of areally extensive sediments of minimal permeability as regional confining units. The existence of these units was determined from analyses of bore-hole geophysical logs. The relative permeability of sediments included in these confining units is estimated to be substantially different (two orders of magnitude or more) from the permeability of sediments included in adjacent units. Therefore, ignoring horizontal flow in these two units should not introduce errors of more than 5 percent (Neuman and Witherspoon, 1969) in a quantitative analysis of ground-water flow. These two confining units, which extend throughout a combined 36 percent of the area underlain by the coastal lowlands aquifer system, were identified by the customary method indicated as criterion 1 above.

The sediments both above and below these two confining units are composed chiefly of numerous sand and clay beds of limited areal extent. Because of a lack of areally extensive clay beds, however, the sediments are assigned to units called permeable zones. The permeable zones can be treated quantitatively as having characteristics equivalent to the inhomogeneous alternating beds (Bear, 1979) because the thickness of the individual beds is much smaller than the linear extent of the beds.

Most of the onshore part of the coastal lowlands aquifer system in Louisiana and about one-half of the aquifer system in southeastern Texas does not contain either zone D confining unit or zone E confining unit (fig. 3). Throughout a substantial part of the Continental Shelf, the top of the geopressured zone (and thus the base of the flow system) is above both of the confining units. Much of the aquifer system containing freshwater is underlain by neither of the two regional confining units, thus necessitating an [illegible] dividing the system. A few examples of the method used to divide the aquifer system are given below along with a discussion of some implications of using the unconventional method. These examples primarily illustrate the application of criterion 3 noted above and focus on three areas, Jasper County, Texas, one in East Baton Rouge Parish, Louisiana, and Houston, Texas.

The example of dividing the coastal lowlands aquifer system at Jasper County, Texas, illustrates the method used where the zone D confining unit does not exist, and pumping is from only one depth. Analysis of bore-hole geophysical logs in and near Jasper County did not indicate any regionally extensive confining units above the zone E confining unit, although this interval in places contains the Burkeville confining unit of previous investigators. The water-level difference across the Burkeville confining unit, as well as across the Evangeline aquifer, is illustrated in figure 4 (modified from Wesselman, 1967, fig. 22). A head change across the Burkeville confining unit of more than 67 ft occurs across an interval of about 430 ft (at the locality of the Burkeville confining unit); thus, a hydraulic-head gradient of about 0.16 ft/ft. The gradient is not very different across one of the fine-grained beds contained within the Evangeline aquifer. A hydraulic-head change of about 19 ft occurs across an interval of about 130 ft in the Evangeline aquifer between 590 and 720 ft below land surface gives a hydraulic-head gradient of about 0.15 ft/ft. A similar gradient is calculated for the fine-grained bed between 920 and 1,050 ft below land surface when using a hydraulic-head value at 920 ft as determined by extrapolating the gradient from 720 ft (dashed lines on fig. 4). Measurements across a similar lithology between 400 and 580 ft below land surface were used for extrapolating the gradient. The vertical gradients indicate that the numerous fine-grained beds (chiefly clay) within the Evangeline aquifer provide about the same vertical resistance as distinct confining units. However, the section above the zone E confining unit is thousands of feet thick in places, and division is necessary for appropriate analysis of ground-water flow.

Thus, at the location in Jasper County, Texas, the sediments above the zone E confining unit were divided into a series of stacked permeable zones without any intervening confining units. These divisions were created such that the pumpage and resultant maximum water-level declines are concentrated near the middle of the delineated unit (permeable zone). These criteria can be satisfied easily when pumpage is generally from one depth zone. Pumpage from several depths places additional restrictions on the divisions.

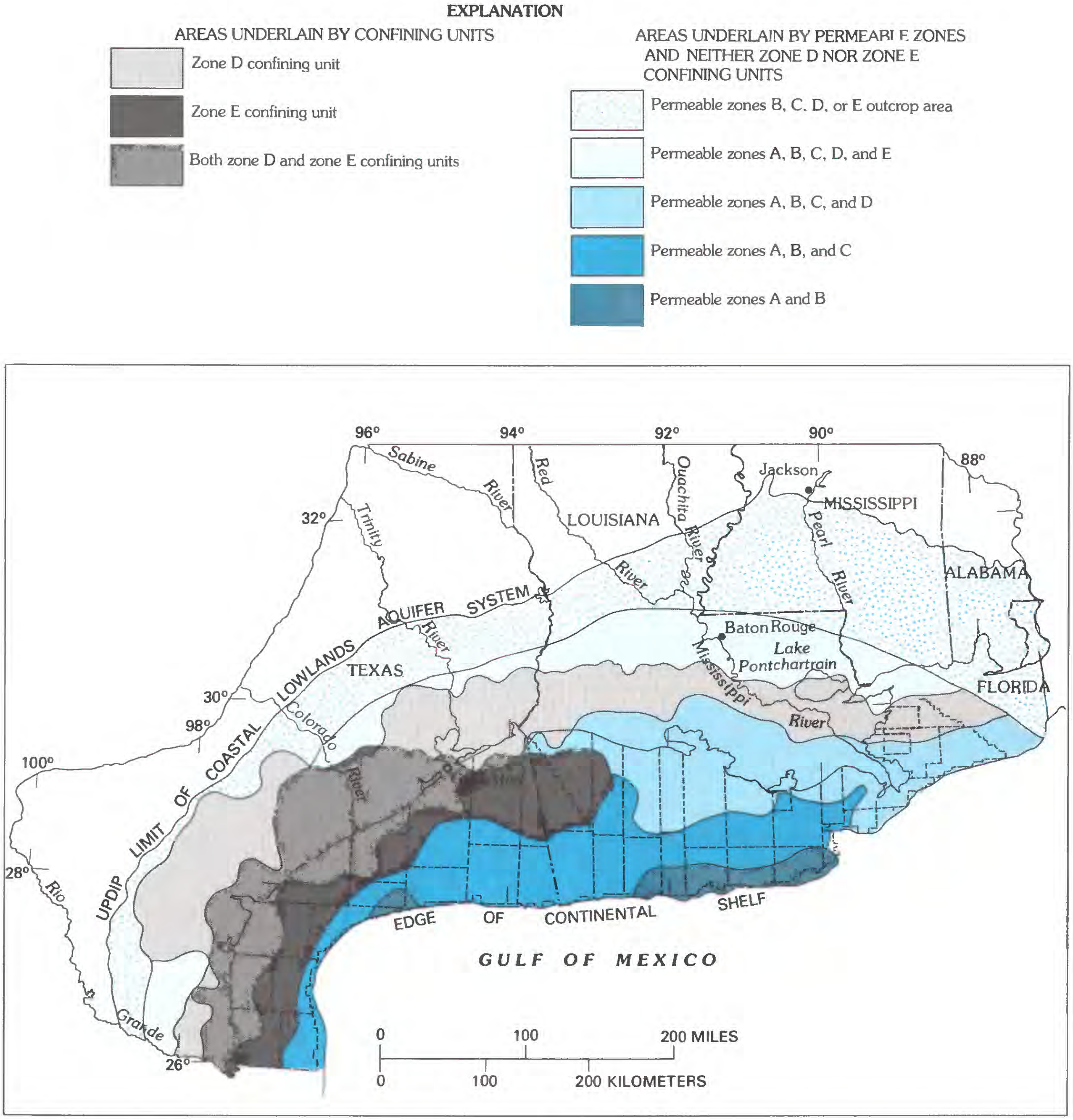

FIGURE 3.—Areas underlain by various combinations of confining units and permeable zones, coastal lowlands aquifer system, south-central United States.

Both of the other two examples are from locations with pumpage from several depths. The example from East Baton Rouge Parish, Louisiana, is from a location where neither zone D confining unit nor zone E confining unit exists. The four permeable zones (A–D) shown in figure 5 are from Weiss and Williamson (1985) and were chosen to minimize the vertical hydraulic-head variation within each zone. Permeable zone E (lower Miocene-upper Oligocene deposits), the lowermost permeable zone in the coastal lowlands aquifer system, occurs throughout East Baton Rouge Parish but is not shown in figure 5 because it is below the depth of the bore-hole geophysical log. There was no hydraulic-head data from the depth interval represented by this lowermost permeable zone (E) in East Baton Rouge Parish; therefore, it was delineated

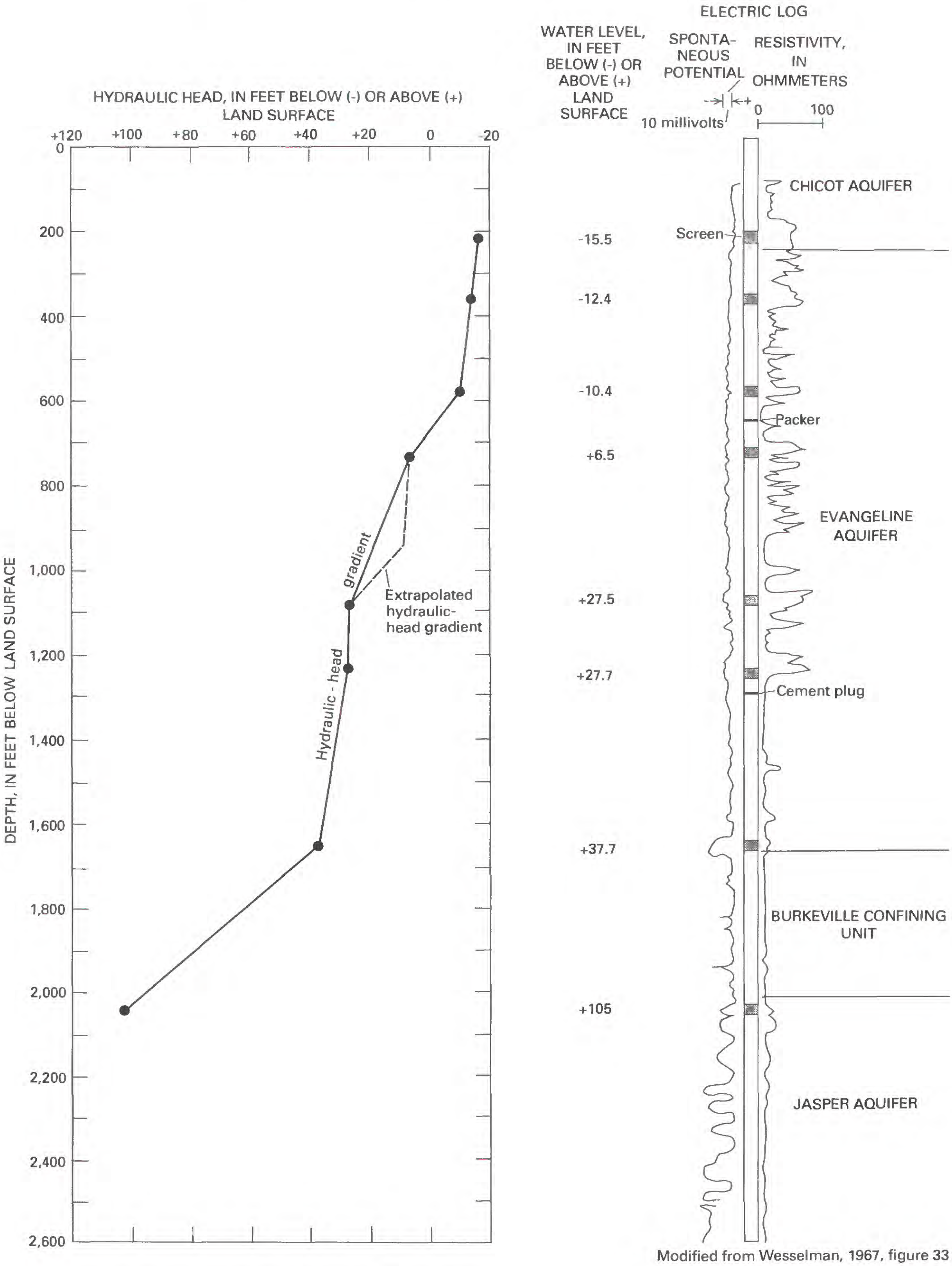

FIGURE 4.—Geohydrologic units and hydraulic-head gradient in the coastal lowlands aquifer system in Jasper County, Texas.

throughout the parish on the basis of criterion 4—namely, extension of units as a constant proportion of total system thickness. Permeable zone E is defined by the existence of zone E confining unit throughout the parish just south of East Baton Rouge Parish. Thus, by adjusting the thickness of permeable zone E from the area of occurrence of zone E confining unit to the south and the head-gradient analysis in East Baton Rouge Parish, a thickness proportion for each permeable zone was determined and used to extend all five permeable zones updip to the inland limit of the aquifer system.

Large variations in hydraulic head with depth due to pumpage also occur near Houston, Texas (fig. 6). The vertical variation in hydraulic head can be minimized in each division if the permeable sediments are divided as shown (Weiss and Williamson, 1985). As in the Baton Rouge area, the zone D confining unit is absent near Houston, but unlike Baton Rouge, the zone E confining unit is present; therefore, the system above the zone E confining unit is divided into four permeable zones. Baton Rouge, Louisiana, and Houston, Texas, are the major pumping centers in the coastal lowlands aquifer system where pumpage occurs from several depth intervals. Thus the permeable zones identified at these two locations influenced the divisions chosen and used throughout much of the coastal lowlands aquifer system.

Variations in hydraulic head with depth can be attributed to natural factors as well as being induced by pumping stresses. The division of sediments into permeable zones was based primarily on the large-scale deflections in the hydraulic-head gradient caused by substantial ground-water pumpage. The variations in hydraulic head with depth due to pumpage can be attributed to several factors. Ideally, the variations are due to differences in vertical hydraulic conductivity (or vertical resistance to flow). If this were the case, the divisions should have some relation to the lithology; however, the depths of pumping intervals probably are the primary factor governing the hydraulic-head distribution. The depths at which the wells are completed probably are related to many other factors in addition to the hydraulic properties of the sediments. The top of the pumping interval likely is determined by the ability of the sediments to transmit enough water to the wells. The bottom of the pumping interval probably is a function of increased costs of drilling deeper, amount of pumping yield desired, and an increase in dissolved-solids concentrations in the water with increasing depth.

A description of the use of criterion 4 and a discussion of several implications of the methods used for division of the aquifer system into geohydrologic unit follows. The effects on the division of the aquifer system of various structural surfaces, outcrop areas, minor pumping centers, and the geopressured zone are the principal topics discussed.

The total number of divisions used primarily was a function of the minimum number of units required for a quantitative regional analysis of ground-water flow in the areas where ground-water pumpage is most extensive. The divisions were extended across the entire aquifer system (criterion 4) by keeping the division a constant proportion of the thickness relative to some structural surface, depending on location. By assuming that the structural surface chosen as a datum is related to depositional patterns, the use of the structural surface as a basis for division decreases the possibility of subdivisions transgressing bedding planes of the sediments. At Houston, the structural surface chosen was the top of the zone E confining unit. At Baton Rouge, zone E confining unit is present nearby at downdip locations. Because zone E confining unit does not crop out, the Vicksburg-Jackson confining unit was chosen as the structural surface for proportioning divisions in places. In downdip areas where the zone D confining unit is present, it was used as the datum from which divisions are measured.

The divisions were extended from the locations of maximum control (Baton Rouge and Houston) to other locations with less information throughout the entire coastal lowlands aquifer system. As the divisions were extended through other pumping centers (such as Lake Charles, and New Orleans, Louisiana), additional restrictions were placed on the thickness of some of the units. The number of divisions remains constant along the strike of the structural surface used; this eliminates abrupt horizontal discontinuities. Consequently, some areas might have more divisions than if they had been considered independently. Areas without any pumpage and, therefore, having either a linear vertical hydraulic-head gradient or relatively minor deflections in the gradient would have more divisions than if they were considered independently. Extending the maximum number of divisions from areas of major control, however, prevents boundary problems and should allow an analysis more consistent with the concept of ground-water flow. The first occurrence of zone E and zone D confining units in middip areas complicates the geometry of the divisions, but these confining units were thinned to a feather edge in these areas where necessary.

An additional constraint on the division of geohydrologic units is the outcrop pattern. The entire thickness of the coastal lowlands aquifer system increases downdip toward the Gulf of Mexico. If the divisions were rigidly restricted everywhere to proportions of depths

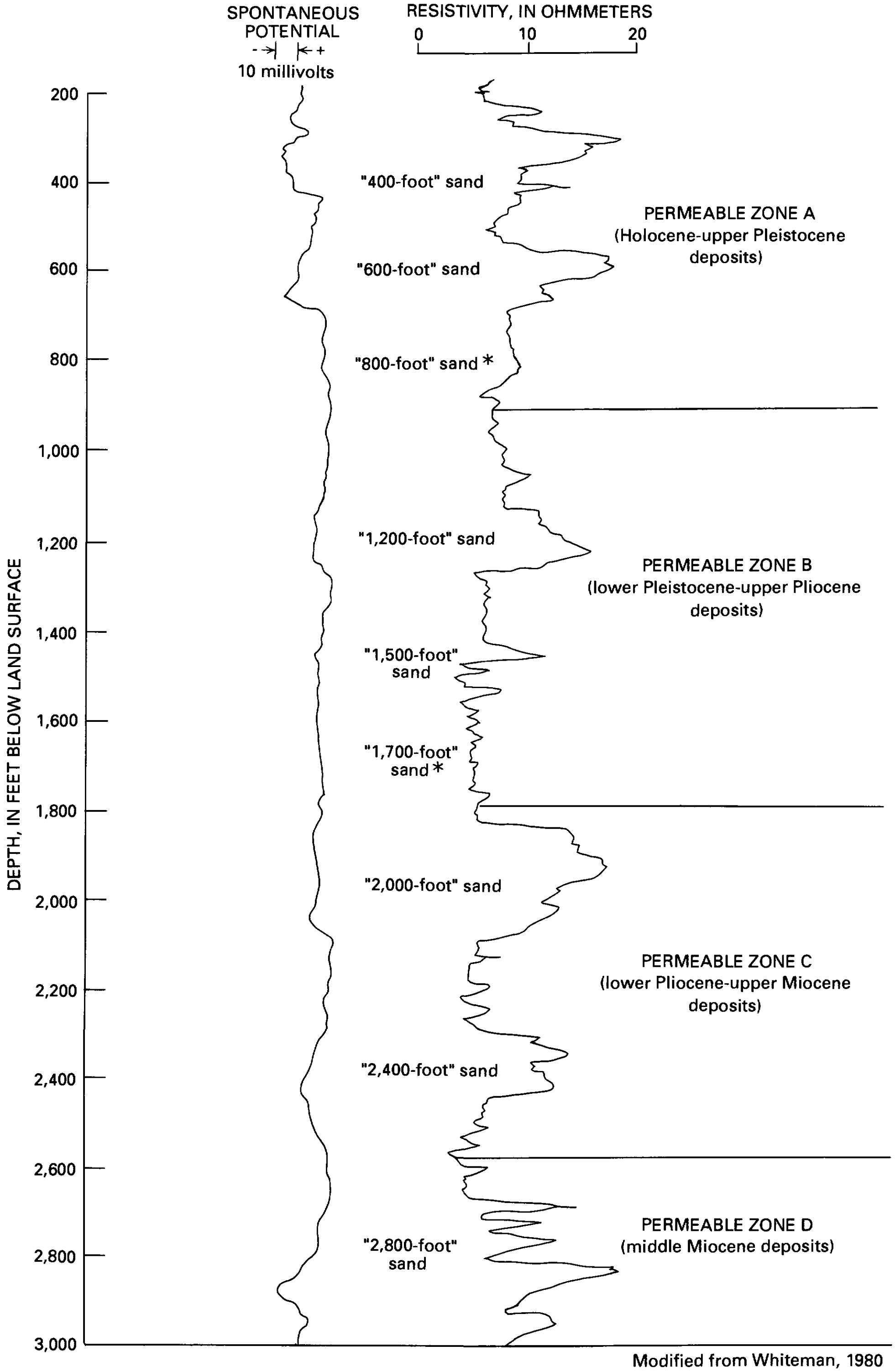

FIGURE 5.—Electric log and geohydrologic units in the coastal lowlands aquifer system in East Baton Rouge Parish, Louisiana. *, sand missing at this location.

to a structural surface and if these proportions were all extended to the maximum updip extent of the aquifer system, all the divisions would converge at a common apex. Converging of units at a common apex contradicts the pattern of sedimentation that characterizes the offlap deposition of the Gulf Coast and also contradicts

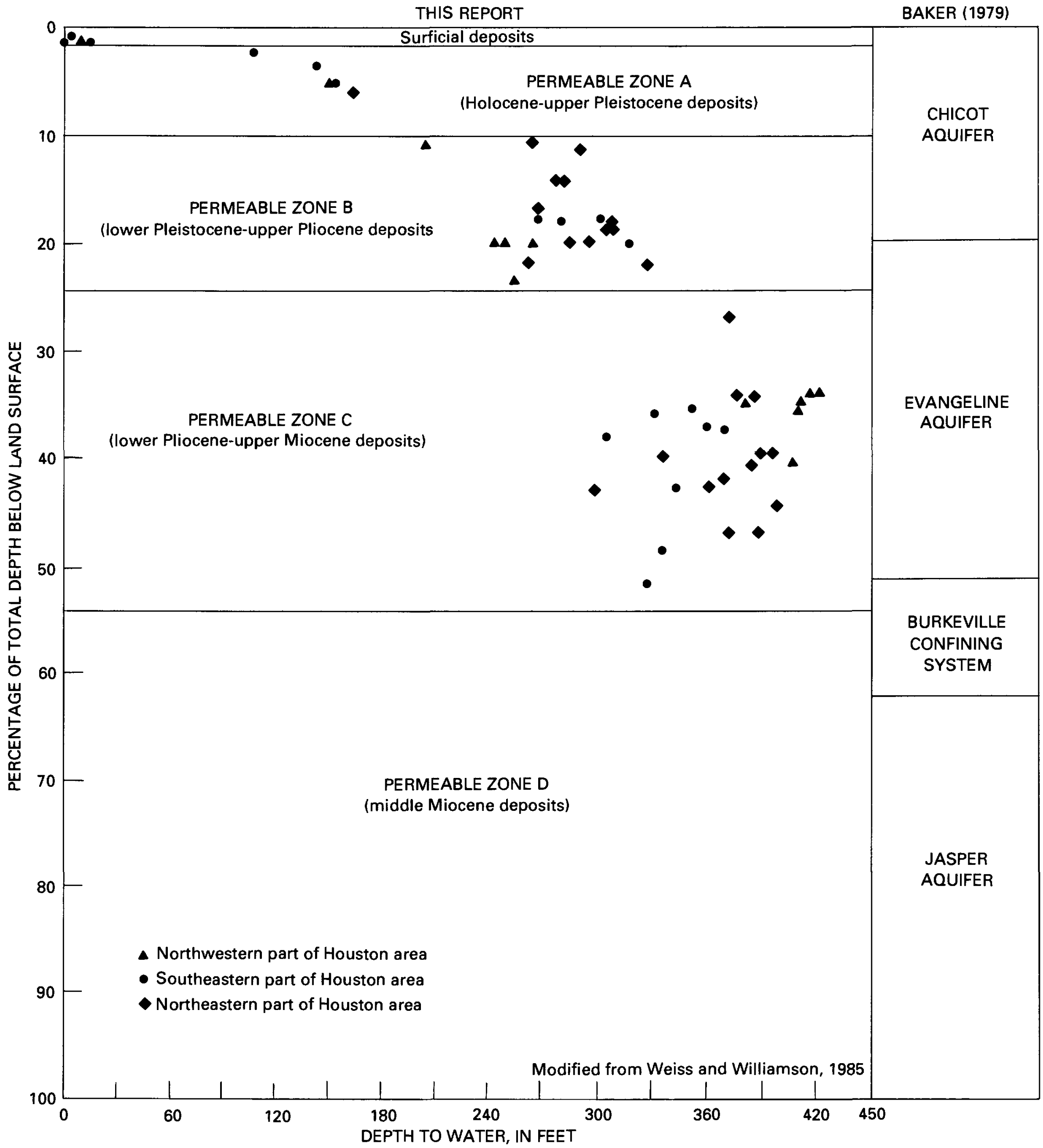

FIGURE 6.—Relation of depth to water and geohydrologic units in the Houston area, Texas.

the concept of allowing direct recharge or discharge at the land surface for each unit, because the entire aquifer system would be blanketed by the same (uppermost) unit. A more reasonable outcrop pattern is a series of bands of successively younger sediments in a gulfward direction, all of which parallel the coastline. The outcrop pattern shown in plate 3 was projected to land surface from downdip areas where data were available for definition of the geohydrologic units. As the divisions were extended to the land surface, the shallowest unit was pinched out first. Continuing updip, the next shallowest unit was pinched out, and so forth, until only the deepest unit occurs at the maximum updip extent.

The downdip extent of most of the geohydrologic units primarily is controlled by the occurrence of the geopressured zone. The top of the geopressured zone increases in depth in a downdip direction until slightly offshore where it becomes shallower in a downdip direction. However, even where the depth to the top of the geopressured zone increases downdip, the increase is at a rate less than the dip of the structural surfaces of the confining units. Therefore, the geohydrologic units are truncated in the subsurface from the bottom up. Because the top of the geopressured zone is not a smooth surface, the deepest unit is truncated in an uneven manner. Here again, had the proportions of thickness been adhered to everywhere, all the divisions would have a thinning trend. This contradicts the conceptual model of the units thickening downdip. The thickening trend was extended so that only the deepest geohydrologic unit reflects the uneven nature caused by the geopressured zone. After that unit is truncated, farther downdip the next highest geohydrologic unit (now the deepest unit) reflects the unevenness, and so forth up the section to the edge of the Continental Shelf where the system is truncated (pls. 4, 5).

The occurrence of growth faults was not directly incorporated in the divisions described in this report. The growth faults, which occur throughout the system, interrupt bedding planes of individual beds. Whiteman (1979) described the effect of the Baton Rouge fault as a hydrologic barrier, and it is probable that other growth faults cause a similar phenomenon. Considering the scale of this regional study, the heterogeneity already incorporated into each unit by the method used in dividing them, and the effort required to incorporate the growth faults, none was given special attention, and thus none appears on the individual maps in this report. However, because growth faults are considered largely responsible for the existence of the geopressured zone, and their presence could be reflected in some of the structure on the lithologic surfaces used for dividing the aquifer system, some effects of their occurrence might be incorporated in delineation of the geohydrologic units.

REGIONAL GEOHYDROLOGIC UNITS

The coastal lowlands aquifer system consists of a thick sequence of sediments of Oligocene, Miocene, Pliocene, Pleistocene and Holocene age. The regional pattern of sedimentation is one of increasing thickness in a downdip, gulfward direction. The permeable zones are truncated downdip by the top of the geopressured zone or at the edge of the Continental Shelf.

The coastal lowlands aquifer system crops out gulfward from the outcrop of the Vicksburg-Jackson confining unit; therefore, the land surface forms the uppermost onshore hydrologic boundary. Maximum relief in the southwestern part of the study area is more than 900 ft in Webb County, Texas; maximum relief in the eastern part is about 500 ft in Jefferson Davis County, Mississippi. As implied in the name, the coastal lowlands aquifer system in much of the area is low lying with land-surface altitudes generally less than 100 ft. In offshore areas, sea level in the Gulf of Mexico is the upper hydrologic boundary.

The base of the coastal lowlands aquifer system is more than 18,000 ft below sea level on the eastern flank of the Terrebonne embayment in southeastern Louisiana (pl. 6). This occurrence is close to the shoreline in the Mississippi River delta. The base becomes shallower offshore because of the occurrence of the geopressured zone and rises to less than 12,000 ft below sea level. The base then becomes deeper farther offshore from Louisiana and declines to depths of more than 15,000 ft below sea level.

The base of the coastal lowlands aquifer system on the eastern flank of the Houston embayment in southwestern Louisiana is more than 14,000 ft below sea level, and on the western flank of the embayment in Texas it is about 11,000 ft below sea level. These occurrences are onshore close to the current shoreline. The base of the aquifer system offshore becomes shallower, rising to about 3,000 ft below sea level due to the occurrence of the geopressured zone.

The base of the coastal lowlands aquifer system is more than 10,000 ft below sea level in the Rio Grande embayment in southern Texas. Offshore, the base of the aquifer system rises relatively uniformly, to depths of about 4,000 ft below sea level at the downdip limit.

The total thickness of the coastal lowlands aquifer system (pl. 6) is the difference between land surface (onshore) or sea floor (offshore) and the base of the aquifer system. Maps of the base of the aquifer system (pl. 6) and the total thickness of the aquifer system (pl. 6) are similar in pattern, both reflecting the irregularity caused by the occurrence of the geopressured zone. The aquifer system generally thickens toward the gulf in the area where the geopressured zone is below the Vicksburg-Jackson confining unit. Thickening is least in the Mississippi salt basin and much greater along the Texas coast. The gulfward thickening trend is interrupted by the occurrence of the geopressured zone, which creates localized abrupt changes in thickness near the shoreline. The average thickness for the coastal lowlands aquifer system is about 6,000 ft.

The percentage and aggregate thickness of sand for the coastal lowlands aquifer system reflects the sand content in all permeable zones and confining units and is shown on plate 6. Sand percentage was calculated by summing the thickness of all sand beds and dividing by the total thickness of the aquifer system at the locations of borehole geophysical logs shown on plate 1. The average sand percentage is about 40 percent. The general pattern of sand percentages shows lobed areas of greater sand percentages extending downdip and coalescing in middip along a band that approximately parallels the current shoreline. These lobed areas presumably represent persistent drainage systems that transported sediment to ancient shorelines where the sediment was redistributed by longshore currents. Sand percentages in the lobes generally are 40 to 60 percent, although local lobes in the Mississippi salt basin in southern Mississippi and Alabama and a lobe extending along the Sabine arch in Texas contain 60 to 80 percent sand. Sand percentages generally are 20 to 40 percent between the lobes of greater sand percentage and updip from the coastal band. Sand percentages along the coastal band generally range from 40 to 60 percent along a narrow strip in southern Texas and along a more extensive band in the Gulf Coast salt basin in southern Louisiana and southeastern Texas. Areas of greater sand percentage also occur along the coastal band in Jasper County, Texas, and St. Martin Parish, Louisiana. The major depocenter for the aquifer system, the Terrebonne embayment, lies in the eastern part of the Gulf Coast salt basin.

Sand percentages decrease to 20 percent or less downdip of the coastal band due to facies change to clay. This area of lesser sand percentage occurs farthest offshore in the Houston embayment and occurs slightly onshore in the Rio Grande embayment in southern Texas, in the Terrebonne embayment in southeast Louisiana, and in Escambia County, Florida. The lesser sand percentage is partly due to facies changes to limestone (Floridan aquifer system) at the eastern boundary of the coastal lowlands aquifer system, in addition to increasing clay content.

Maximum sand thickness is more than 7,000 ft on the east and west flanks of the Terrebonne embayment in southern Louisiana. In Texas, a maximum sand thickness of more than 5,000 ft occurs in the Houston embayment, and more than 4,000 ft of sand occurs in the Rio Grande embayment. In all these areas, the maximum sand thickness occurs onshore and coincides with both the coastal band of maximum sand percentages and the maximum thickness of the aquifer system.

The divisions of the coastal lowlands aquifer system described in this report are: (1) permeable zone A (Holocene–upper Pleistocene deposits), (2) permeable zone B (lower Pleistocene–upper Pliocene deposits), (3) permeable zone C (lower Pliocene-upper Miocene deposits), (4) zone D confining unit, (5) permeable zone D (middle Miocene deposits), (6) zone E confining unit, and (7) permeable zone E (lower Miocene–upper Oligocene deposits).

PERMEABLE ZONE A (HOLOCENE–UPPER PLEISTOCENE DEPOSITS)

Permeable zone A (Holocene–upper Pleistocene deposits) underlies an area of about 120,000 mi^2 and is the shallowest geohydrologic unit in most areas of the coastal lowlands aquifer system. Its upper surface onshore is land surface, and its upper surface offshore is the sea floor. Because there is no regional confining unit to form a boundary between this unit and the underlying permeable zone B, the boundary was primarily defined by sharp changes in vertical hydraulic gradient and local lithology of the sediment as discussed previously (figs. 5, 6). Permeable zone A is equivalent to about the upper one-half or more of the Chicot aquifer in Texas and southwestern Louisiana (fig. 6, pls. 4, 7, 8), and is also equivalent to the "200-foot," "400-foot," and "800-foot" sands at Baton Rouge, Louisiana (fig. 5). At Lake Charles, Louisiana, permeable zone A is equivalent to the "200-foot," "500-foot," and "700-foot" sands and in the New Orleans area, Louisiana, to the shallow "200-foot," "400-foot," and "700-foot" sands.

Permeable zone A extends updip near the Mississippi River to the northern boundary of the coastal lowlands aquifer system as a relatively thin blanket of sediments that truncates all underlying geohydrologic units (pl. 3). Permeable zone A is a southern extension of the Mississippi River Valley alluvial aquifer of the Mississippi embayment aquifer system from the outcrop of the Vicksburg-Jackson confining unit southward in a band about 30 to 50 mi wide as shown on plate 3.

The average thickness of permeable zone A is about 700 ft. Maximum thickness is more than 1,200 ft in part of the Terrebonne embayment offshore from Louisiana (pl. 9). The zone is somewhat thinner in Texas, having a thickness of slightly more than 900 ft offshore in the Houston embayment and slightly more than 700 ft a short distance offshore in the southern part of the Rio Grande embayment. The zone is less than 200 ft thick in a narrow band that extends farther updip near the Mississippi River.

Unlike the underlying geohydrologic units, the thinning of zone A toward its downdip limit is not due to the top of the geopressured zone, because the geopressured zone does not exist above the top of the underlying permeable zone B. Rather, the thinning is due to the configuration of the sea floor, which is more uniform than the top of the geopressured zone. Therefore, the thinning of permeable zone A is rather uniform relative to the thinning of the underlying geohydrologic units.

The percentage and aggregate thickness of sand in permeable zone A is shown on plate 9. The pattern of sand percentages for this zone differs greatly from that of the deeper, underlying zones. The distinctive coastal band of greater sand percentages in middip areas that are present in the deeper permeable zones does not exist in this zone. Perhaps this is because this thinner zone incorporates sediment deposited during a much shorter time interval that does not reflect the persistence of longshore currents existing during the time of deposition.

In Louisiana, maximum sand percentages of greater than 80 percent occur at the updip limits of permeable zone A and extend downdip in a lobate pattern. Sand percentages gradually decrease downdip, although greater sand percentages exist far offshore in lobes. A large lobe extends into the Terrebonne embayment, and another occurs offshore from southwestern Louisiana. Sand percentages decrease markedly near the edge of the Continental Shelf where they generally are less than 20 percent.

In Texas, the pattern of sand percentages of permeable zone A is similar to that in Louisiana, although not quite as pronounced. Lobes of sand percentages of 60 to 80 percent extend downdip in the Houston and Rio Grande embayments, and sand percentages are greater than 80 percent in places. These lobes do not extend as far downdip as the lobes in Louisiana, and sand percentages decrease to less than 20 percent in a relatively short distance offshore. A large area of 40 to 60 percent sand extends farther offshore between the Houston and Rio Grande embayments, downdip from the San Marcos arch.

Sand percentages of less than 20 percent occur in relatively few areas onshore. One area of sand percentages of less than 20 percent occurs near the updip extent of permeable zone A in southern Texas to the east of the South Texas salt basin; a second area occurs near the updip extent of the zone in southern Mississippi due to facies changes in the vicinity of the Hancock arch and extends offshore farther downdip. These occurrences generally are the exception, as the average sand percentage of permeable zone A is slightly more than 60 percent, which is considerably greater than that for any of the other permeable zones. Because permeable zone A is thin, it has relatively little effect on the average sand percentage for the entire aquifer system.

Maximum sand thickness is more than 1,000 ft offshore from Louisiana, as well as onshore, and is coincident with the area where sand percentages are greater than 80 percent. Maximum sand thickness in Texas is only slightly more than 500 ft in the Rio Grande embayment and slightly more than 400 ft in the Houston embayment and occurs where the zone is very thick.

PERMEABLE ZONE B (LOWER PLEISTOCENE–UPPER PLIOCENE DEPOSITS)

Permeable zone B (lower Pleistocene-upper Pliocene deposits) directly underlies permeable zone A without an intervening, regionally mappable confining unit in an area of about 130,000 mi^2. As with the other permeable zones of the coastal lowlands aquifer system, it is composed chiefly of interbedded sand and clay of limited areal extent. The boundaries between permeable zone B and the underlying and overlying permeable zones were defined by drastic changes in vertical hydraulic gradients and local lithology of the sediments. The two areas with the most substantial deflections in vertical hydraulic gradients are at Baton Rouge, Louisiana, and near Houston, Texas.

The relation of this permeable zone to the ages of the sediments is shown on plates 7 and 8. Most of the sediments it contains are of early Pleistocene or late Pliocene age. This zone in places is equivalent to the upper part of the Evangeline aquifer (the part not included in the underlying permeable zone) and in places is equivalent to as much as about one-half of the Chicot aquifer (fig. 6, pls. 4, 7, 8). In Baton Rouge, Louisiana, permeable zone B includes the “1,200-foot,” “1,500-foot,” and “1,700-foot” sands (fig. 5).

The altitude and configuration of the top of permeable zone B is shown on plate 10. The deepest occurrence is more than 1,200 ft below sea level at its downdip limit in the Terrebonne embayment offshore from Louisiana. The data values used for contours shown on plate 10 are equal to land-surface or sea-floor altitude minus the thickness of permeable zone A as noted previously. Thicknesses were interpolated for each square of a regular grid from thickness data at locations of the bore-hole geophysical logs shown on plate 1. Average land-surface altitude was estimated from digital topographic data for each square of the grid as described by Williams and Williamson (1989). The squares of the grid have sides that are 5 mi in length.

The average thickness of permeable zone B is about 1,900 ft. Maximum thickness is about 5,650 ft in part of the Terrebonne embayment offshore from Louisiana, more than 4,000 ft in the Houston embayment offshore from Texas, and only about 2,000 ft in the Rio Grande embayment offshore from southern Texas (pl. 10). In general, the thickness increases downdip from the outcrop to near the edge of the Continental Shelf. The geopressured zone truncates the base of this zone in a band about 20 mi wide offshore from Louisiana near the edge of the Continental Shelf and in an isolated area offshore from Texas.

The percentage and aggregate thickness of sand in permeable zone B is shown on plate 10. The average sand percentage is about 50 percent, less than the average for the overlying permeable zone A, and the sand-percentage distribution has a pattern different than that of permeable zone A and more like the underlying permeable zones. A coastal band of greater sand percentage exists in middip areas across southern Louisiana. The sand percentage decreases from 60 percent in most updip areas of Texas to less than 20 percent downdip on the Continental Shelf. In Texas, sand percentages greater than 80 percent occur in outcrop areas in Victoria County south of the San Marcos arch, in San Jacinto County on the eastern flank of the Houston embayment, and in Newton County at the Texas-Louisiana border. This latter area also extends to adjacent parishes of Louisiana. These areas extend downdip as lobes beyond the outcrop for only a short distance before decreasing in sand percentage. Sand percentages near the coastline in Texas are 20 to 40 percent and become less than 20 percent offshore.

Sand percentages in Louisiana and southern Mississippi generally range from 40 to 60 percent in middip along a coastal band that crosses the Terrebonne embayment. Farther downdip sand percentages decrease to less than 20 percent in offshore areas. The coastal band of greater sand percentages connects with lobes extending downdip from the outcrop along the Louisiana-Texas State line, and in Amite, Pike, and Walthall Counties, Mississippi. In southeastern Mississippi sand percentages are less than 20 percent in the outcrop area due to facies changes occurring on the Wiggins anticline. This trend in lesser sand percentages also occurs at the far-eastern edge of the study area offshore from Alabama.

Maximum sand thickness is nearly 3,000 ft in several areas offshore from Louisiana where large thicknesses occur along the coastal band of greater sand percentages. In Texas, maximum sand thicknesses occur in lobes of greater sand percentages in the Rio Grande embayment and in the Houston embayment. Although sand percentages are large (greater than 60 percent), these occurrences are far enough onshore (updip) that the zone is relatively thin. Consequently, maximum sand thicknesses are only about 800 ft in the Rio Grande embayment and about 700 ft in the Houston embayment.

PERMEABLE ZONE C (LOWER PLIOCENE–UPPER MIOCENE DEPOSITS)

Permeable zone C (lower Pliocene–upper Miocene deposits), which has an areal extent of about 140,000 mi^2, underlies permeable zone B without an intervening, regionally mappable confining unit. The boundary between permeable zones C and B was defined by sharp changes in hydraulic gradients and local lithology of the sediment as described previously. Permeable zone C overlies zone D confining unit throughout the area where the confining unit is recognized (fig. 3) on bore-hole geophysical logs. Zone D confining unit exists in only part (about 20 percent) of the area underlain by permeable zone C. Throughout the remainder of the area underlain by permeable zone C, it directly overlies permeable zone D without an intervening, regionally mappable confining unit. The boundary between permeable zone C and the underlying permeable zone D was also defined by sharp contrasts in hydraulic gradients and local lithology of the sediments as described previously. Two areas with substantial deflections in the vertical hydraulic gradients are at Baton Rouge, Louisiana, and near Houston, Texas.

The relation of this permeable zone to contiguous geohydrologic units from the outcrop area to the point where it is truncated by the geopressured zone is shown on plate 4. Because the underlying zone D confining unit is defined on lithology, the lower boundary of permeable zone C rises as the sediments become clayey in a downdip direction, which causes a slight thinning of the permeable zone. The ages of the sediments making up permeable zone C are shown on plates 7 and 8. Although this permeable zone contains sediments of varying ages, the predominant age is late Miocene and early Pliocene. Permeable zone C is equivalent to at least the lower 50 percent (in places as much as about 80 percent) of the Evangeline aquifer (fig. 6, pls. 4, 7, 8) and to the "2,000-foot" and "2,400-foot" sands at Baton Rouge, Louisiana (fig. 5).

The altitude and configuration of the top of permeable zone C is shown on plate 11. The deepest occurrence is almost 7,000 ft below sea level in part of the Terrebonne embayment offshore from Louisiana, and the depth is almost 3,000 ft below sea level offshore from southern Texas in the Rio Grande embayment. The top of this permeable zone becomes steadily deeper across the Houston embayment of southeastern Texas.

The average thickness of permeable zone C is about 2,000 ft. Maximum thickness is more than 6,300 ft in the Terrebonne embayment offshore from Louisiana (pl. 11). Thicknesses of almost 5,000 ft occur relatively close to the shoreline in the Houston embayment, with a thinning occurring farther offshore. A thickness of about 3,500 ft occurs in the Rio Grande embayment offshore from Texas. The thick sequences of water-bearing strata offshore from Texas differ from those offshore from Louisiana in that they occur updip from the geopressured zone. Permeable zone C is thinner offshore from Texas due to its greater distance from the depocenter of the coastal lowlands aquifer system, which is offshore from Louisiana, and the gradation of sand in the basal part of the permeable zone into clay of the underlying zone D confining unit. The occurrence of the underlying confining unit in Texas causes an irregular trend in thickness as compared to Louisiana, Mississippi, and Alabama, where zone D confining unit is absent and a relatively uniform increase in thickness occurs. Thinning of this permeable zone in middip is due to the underlying zone D confining unit in the subsurface (pl. 4). Permeable zone C subsequently thickens farther downdip and thins again due to the occurrence of the geopressured zone.

The downdip limit of permeable zone C (pl. 11) is the line along which the top of the geopressured zone intersects the top of the permeable zone. The downdip limit occurs offshore, being closest to the shoreline near the Mississippi River delta and farthest from the shoreline in the Houston embayment.

The geopressured zone begins to truncate the base of permeable zone C at the downdip limit of zone D confining unit that is offshore from Texas and is offshore from westernmost Louisiana (fig. 3, pl. 11). East of the area where zone D confining unit exists the geopressured zone begins to truncate the base of permeable zone C at the downdip limit of the underlying permeable zone D (fig. 3, pls. 11, 14). The top of the geopressured zone rises gradually in the Houston embayment, resulting in large irregularities in thickness of permeable zone C. The geopressured zone rises abruptly in the Rio Grande embayment offshore from southern Texas.

The percentage and aggregate thickness of sand for permeable zone C is shown on plate 11. The average sand percentage is about 45 percent, slightly smaller than the sand percentage of the overlying permeable zone B. A characteristic coastal band of greater sand percentage exists in this permeable zone onshore across southern Louisiana and to the southwest along the Texas coast. Sand percentages of 60 to 80 percent extend from the vicinity of Lake Pontchartrain in eastern Louisiana to northeastern Cameron Parish in southwestern Louisiana. Sand percentages of 40 to 60 percent are characteristic of the coastal band of greater sand percentages from Cameron Parish, Louisiana, on to the southwest along the Texas coast. The maximum sand percentages in permeable zone C generally are 40 to 60 percent in Texas and 60 to 80 percent in most of Louisiana. Sand percentages decrease to 40 to 60 percent in southeastern Mississippi and to 20 to 40 percent in southern Alabama.

Sand percentages greater than 80 percent occur in some outcrop areas in Mississippi on the northeast flank of the Wiggins anticline near the Mississippi-Alabama State line and to the northwest of the Wiggins anticline at the Mississippi-Louisiana State line. An area of sand percentages less than 20 percent in Mississippi extends downdip between these two areas. Sand percentages in outcrop areas in Louisiana are mostly less than 60 percent, but are as much as 60 to 80 percent near the Louisiana-Mississippi State line and near the Louisiana-Texas State line. Other areas with sand percentages of 60 to 80 percent occur in the outcrop in Texas near the head of the Houston embayment and on the flanks of the South Texas salt basin. Sand percentages are less than 20 percent in outcrop areas near the middle of the South Texas salt basin and near the Rio Grande.

The areas of greater sand percentage extend downdip from the outcrop areas in lobes that coalesce with the longshore band of sand deposits. Sand percentages between the lobes generally are 20 to 40 percent, although locally they may be less than 20 percent. The area of greater sand percentage near the southern part of the Mississippi-Louisiana State line is an exception in that the lobes are apparently interrupted by areas of lesser sand percentage. These lobes do not extend to the longshore coastal band. Sand percentages decrease downdip from the coastal band and are less than 20 percent along the entire downdip limit of the permeable zone. The farthest area offshore with 40 to 60 percent sand occurs in the Houston embayment. However, sand percentages decrease abruptly along the flanks of this feature, making this one of the farthest updip areas (although downdip from the coastal band) with sand percentages less than 20 percent.

Maximum sand thickness for permeable zone C is about 3,300 ft in the Terrebonne embayment in Louisiana. This thickness occurs in the coastal band and is a relatively short distance updip from the maximum total thickness for the permeable zone. Other areas of large sand thickness occur offshore from Texas. A sand thickness of more than 1,700 ft occurs in the Houston embayment in a lobe of greater sand percentages extending far offshore close to the area of maximum thickness. A sand thickness of more than 1,600 ft occurs in the Rio Grande embayment, also within the coastal band of greater sand percentages but relatively far from the maximum thickness farther south in the Rio Grande embayment. The maximum thickness of the permeable zone in the Rio Grande embayment occurs in an area of minimum sand percentage and, therefore, has a relatively small sand thickness.

ZONE D CONFINING UNIT

The zone D confining unit separates permeable zones C and D in Texas and in a small area offshore from Louisiana. These are the only areas where a thick, massive clay of regional extent could be identified. A geophysical log from San Patricio County, Texas, illustrating the thick clay identified as the zone D confining unit is shown on plate 12. The zone D confining unit does not crop out at the land surface. The relation of the zone D confining unit to permeable zones is shown on plates 4 and 7. Geohydrologic section *F–F′* (pl. 7), which generally follows the strike of the geohydrologic units, illustrates the pinching out of the zone D confining unit to the east.

The altitude and configuration of the top of the zone D confining unit are shown on plate 13. The shallowest occurrence is about 1,000 ft below sea level downdip from the San Marcos arch in Jackson County, Texas, and coincides with its farthest updip occurrence. The deepest occurrence is offshore from Louisiana at the eastern flank of the Houston embayment, where its top is about 9,000 ft below sea level. The updip limit in this area also is offshore, and the entire unit, therefore, occurs offshore in this area. The deepest occurrence on the western flank of the Houston embayment is almost 7,500 ft below sea level; in the Rio Grande embayment the top of the zone D confining unit is about 5,500 ft below sea level. In both of these areas the unit occurs onshore as well as offshore.

The average thickness of the zone D confining unit is about 1,000 ft. The maximum thickness is almost 2,000 ft in the Rio Grande embayment offshore from Texas (pl. 13). The confining unit is about 1,800 ft thick on both the western flank of the Houston embayment offshore from Texas and on the eastern flank offshore from Louisiana. Large thicknesses also occur onshore, particularly in Calhoun County, Texas, where the thickness is about 1,900 ft.

The downdip limit of the zone D confining unit occurs offshore, approximately paralleling the shoreline (pl. 13), and is the line along which the top of the geopressured zone intersects the top of the confining unit. The downdip limit is closest to the shoreline in the Rio Grande embayment in southern Texas and extends farthest offshore in the Houston embayment near the offshore extension of the Texas-Louisiana State line where the updip limit also trends offshore.

The farthest updip occurrence of the geopressured zone represents the downdip limit of the underlying permeable zone D. The top of the geopressured zone rises fairly abruptly close to the downdip limit of the zone D confining unit across most of the area offshore from Texas, thereby causing a relatively abrupt thinning. The top of the geopressured zone rises gradually where the zone D confining unit is farthest offshore on the eastern flank of the Houston embayment. Thinning of the confining unit is much less abrupt in this area.

Irregularities in thickness of the zone D confining unit occur in the area where the top of the geopressured zone truncates the base of the confining unit. However, irregularities in thickness also exist because of an irregular structural surface and the criteria used to define the confining unit. The confining unit is defined by the occurrence of a regionally persistent, thick, massive clay with sand percentages generally less than 10 percent. However, in some areas correlation was particularly difficult, and strata with relatively large sand percentages were mapped as part of this unit. This was done, for example, in the Houston embayment in Brazoria County, Texas, where sand percentages exceed 40 percent and in the Rio Grande embayment in Kleberg County, Texas, where sand percentages exceed 20 percent. The nonuniformity of this unit is reflected on plate 13 and is well illustrated on plates 4 and 7.

PERMEABLE ZONE D (MIDDLE MIOCENE DEPOSITS)

Permeable zone D (middle Miocene deposits) underlies about 120,000 mi^2 and overlies the zone E confining unit where present or is in direct contact with permeable zone E (lower Miocene–upper Oligocene deposits), where no regional confining unit separates the two permeable zones. In part of Texas and in a small area offshore from southwestern Louisiana, permeable zone D is overlain by the zone D confining unit. Thus, the thickness of permeable zone D is directly related to the occurrence of the underlying and overlying confining units where both are present, about 13 percent of the area underlain by permeable zone D. In about 50 percent of the area underlain by permeable zone D, neither the zone D confining unit nor zone E confining unit is present (fig. 3). Therefore, permeable zone D is directly overlain by permeable zone C or directly underlain by permeable zone E, or both, without an intervening, regionally mappable confining unit. The boundaries between these permeable zones, in areas without confining units, were defined by drastic changes in hydraulic gradients and the local lithology of the sediments, as previously described.

The relation of permeable zone D to adjacent permeable zones and confining units from its outcrop in southern Louisiana to its truncation downdip by the occurrence of the geopressured zone is shown on plate 5. The relation of permeable zone D to adjacent geohydrologic units in Texas is shown on plate 4. Thickness of permeable zone D increases downdip to the abrupt truncation of the zone by the geopressured zone. The relation of permeable zone D to time-stratigraphic units and to previously defined geohydrologic units is shown on plates 7 and 8. Permeable zone D is approximately equivalent to the Jasper aquifer in Texas and southwestern Louisiana, as shown in figure 6 and on plates 4, 7, and 8, and includes the "2,800-foot" sand at Baton Rouge, Louisiana, as shown in figure 5.

The altitude and configuration of the top of permeable zone D is shown on plate 14. The deepest occurrence is about 12,500 ft below sea level in the Terrebonne embayment offshore from southeastern Louisiana. The unit is not quite as deep in Texas, being almost 9,550 ft below sea level in the Houston embayment and about 6,700 ft below sea level in the Rio Grande embayment. The top of permeable zone D slopes very gently gulfward in southeastern Mississippi and southern Alabama near the eastern boundary of the coastal lowlands aquifer system.

The average thickness of permeable zone D is about 1,800 ft. Maximum thickness is about 7,500 ft in the Terrebonne embayment in southeastern Louisiana and about 6,200 ft in Cameron Parish in southwestern Louisiana (pl. 14). Permeable zone D generally is thinner in Texas than in Louisiana, partly due to the lesser total thickness of the aquifer system in Texas and partly due to the upper part of the zone grading into clay of the overlying confining unit. The zone is thin far downdip near the eastern edge of the aquifer system in southern Alabama.

As with the other permeable zones, the downdip limit of permeable zone D is the line along which the top of the geopressured zone intersects the top of the permeable zone. The downdip limit is slightly onshore at the Rio Grande in southern Texas and remains offshore in the rest of the study area, although it is near the shoreline in part of the Terrebonne embayment in southeastern Louisiana. The downdip limit is farthest offshore in parts of the Terrebonne embayment, as shown on plate 14.

The farthest updip occurrence of the geopressured zone (pl. 14) coincides with the downdip limit of the underlying zone E confining unit; downdip of this line the top of the geopressured zone forms the base of permeable zone D. The updip limit of the geopressured zone is close to the shoreline in southern Texas, then it immediately trends offshore to the Texas-Louisiana State line where it trends back onshore. It continues onshore across the Terrebonne embayment in Louisiana and trends offshore again at Breton Sound in southeastern Louisiana.

The area in which the top of the geopressured zone rises most abruptly is offshore from Texas. The area in which the top of the geopressured zone rises less abruptly is in Louisiana in the Terrebonne embayment. As the top of the geopressured zone is uneven, abrupt irregularities in thickness of permeable zone D occur within the area where the top of the geopressured zone truncates the base of the permeable zone.

The percentage and aggregate thickness of sand for permeable zone D is shown on plate 14. The average sand percentage is about 45 percent. Sand percentages generally increase downdip to a maximum in a band that approximately parallels the shoreline and then decrease further downdip. The band of substantial sand percentage occurs onshore but close to the shoreline in the Rio Grande embayment in southern Texas. Eastward, it is farther onshore except where it extends slightly offshore in southeastern Mississippi and southern Alabama.

Sand percentages in the outcrop area of permeable zone D generally are 40 to 60 percent, but the percentage in outcrop is very variable. In much of the outcrop area, the sand percentage is 60 to 80 percent and is greater than 80 percent in places; however, the sand percentage in other areas is 20 to 40 percent, and in a few areas it is less than 20 percent.

Permeable zone D also has a lobate pattern of sand distribution downdip from the outcrop. A large lobe of 60 to 80 percent sand extends downdip along the Louisiana-Texas State line. Another large lobe of 40 to 60 percent sand extends downdip near the Mississippi River. A large lobe extends downdip from outcrop in southern Mississippi and connects with a smaller lobe originating in outcrop near the Mobile graben of southern Alabama. The two lobes along State borders coalesce in the coastal band where sand percentages generally are 40 to 80 percent; however, the lobes in southern Mississippi and southern Alabama are interrupted by an arcuate band of lesser sand percentages, generally less than 20 percent. This arcuate band begins in outcrop near the Mississippi-

Louisiana State line and extends southeast across Mississippi to the Wiggins anticline.

Sand percentages decrease downdip from the coastal band to 20 to 40 percent. Further downdip, sand percentages are less than 20 percent in much of the area, particularly in the Terrebonne embayment of Louisiana. Areas with minimum sand content extend relatively far updip in southern Alabama and Mississippi due to facies changes near the eastern edge of the study area. An exception occurs offshore of Matagorda County, Texas, between the Houston and Rio Grande embayments and downdip from the San Marcos arch. In this area, sand percentages in an isolated area are 60 to 80 percent near the downdip limit of this permeable zone.

Maximum sand thickness for permeable zone D is about 3,000 ft in several areas in the Gulf Coast salt basin in Louisiana. These areas occur along the coastal band where the permeable zone is fairly thick, and sand percentages are as much as 60 to 80 percent. However, these areas of greater sand percentages are not exactly coincident with the maximum unit thickness, which occurs farther downdip. Maximum sand thicknesses in Texas are greater than 2,500 ft in the Rio Grande embayment, about 2,000 ft in the Houston embayment, and more than 2,000 ft directly downdip from the San Marcos arch. This latter area is a short distance offshore slightly downdip of the coastal band of greater sand percentages and is due to the large thickness of permeable zone D.

ZONE E CONFINING UNIT

The zone E confining unit lies between permeable zones D and E in the downdip part of the coastal lowlands aquifer system along the coastline. A bore-hole geophysical log from Nueces County, Texas, illustrates the contrast in lithology that is the basis for definition of this zone (pl. 12). The zone E confining unit is about 930 ft thick at this location. The inter-bedded nature of the overlying and underlying sediments and the contrast in lithology at the base of the aquifer system (the top of the Vicksburg-Jackson confining unit) also are illustrated on plate 12.

The zone E confining unit does not extend to the land surface and overlies permeable zone E throughout much of Texas and coastal Louisiana (fig. 3, pl. 3). In updip areas, permeable zone E is directly overlain by permeable zone D without an intervening, regionally mappable confining unit. As noted previously, the zone D confining unit also pinches out updip; therefore, the permeable zones of the coastal lowlands aquifer system are not separated by an intervening confining unit in much of the study area (about 64 percent). The zone E confining unit is in places closely coincident with the Anahuac Formation (Ellisor, 1944) (pls. 4, 7). As with the underlying "Frio" Formation, the age of the Anahuac Formation is uncertain.

The altitude and configuration of the top of the zone E confining unit are shown on plate 15. This confining unit comes closest to the land surface in southern Texas near the San Marcos arch and the Mirando-Provident City fault zone (pl. 2). In this area, the top of the zone E confining unit is as shallow as 200 ft below land surface. A bore-hole geophysical log from Live Oak County, Texas (pl. 12), illustrates the occurrence of the zone E confining unit directly on top of the Vicksburg-Jackson confining unit without the intervening permeable zone. At this location, the top of the zone E confining unit is about 770 ft below land surface or 360 ft below sea level. However, in most of the area, the altitude of the top of the confining unit is more than 4,000 ft below sea level. In the Rio Grande embayment and in the eastern part of the Houston embayment, the top of this confining unit is deeper than 10,000 ft below sea level and is more than 12,000 ft below sea level in the Terrebonne embayment of southeastern Louisiana.

The average thickness of the zone E confining unit is about 1,000 ft. Maximum thickness is about 4,000 ft on the eastern flank of the Houston embayment near the Louisiana-Texas State line and on the western flank of the Houston embayment in Brazoria County, Texas (pl. 15). The next thickest area of this confining unit is in Calhoun County, Texas, where it has a maximum thickness of about 3,300 ft. In the Rio Grande embayment in southern Texas, the maximum thickness of the confining unit is about 2,700 ft. In Louisiana, a maximum thickness of about 3,000 ft occurs near New Orleans.

The downdip limit of the zone E confining unit parallels the shoreline slightly offshore from Texas, trends onshore across southern Louisiana, and is also offshore at Chandeleur Sound near southeastern Louisiana. This confining unit occurs only offshore at the eastern end of the study area; however, this occurrence is based on extrapolations across an area with few data.

The farthest updip occurrence of the geopressured zone in this confining unit (pl. 15) represents the downdip limit of the underlying permeable zone E. The farthest updip occurrence of the geopressured zone is close to the downdip limit of the zone E confining unit offshore in the Rio Grande embayment, indicating that the top of the geopressured zone rises abruptly. The top of the geopressured zone rises less abruptly elsewhere in Texas and southeastern Louisiana. Irregularities in the thickness of the zone E confining unit are due to the uneven nature of the top of the geopressured zone in those areas where the base of the confining unit is truncated by the top of the geopressured zone.

Variations in thickness of the zone E confining unit occur in areas updip of the geopressured zone and are due to structural and depositional effects. The zone E confining unit is defined as a thick, regional, massive clay unit. Thin beds of sand occur within the unit, but sand percentages generally are less than 10 percent. An exception is in San Patricio and Refugio Counties in southern Texas where the zone E confining unit was extended across an area with sand percentages of about 20 percent.

PERMEABLE ZONE E (LOWER MIOCENE–UPPER OLIGOCENE DEPOSITS)

Permeable zone E (lower Miocene–upper Oligocene deposits) is the lowermost geohydrologic unit of the coastal lowlands aquifer system and underlies about 90,000 mi^2. Definition of this zone was determined in most of the area by the presence of the underlying Vicksburg-Jackson confining unit and in about one-half of the area by the overlying zone E confining unit. However, because the overlying zone E confining unit does not extend to the land surface, the updip occurrence of permeable zone E and the boundary between permeable zone E and the overlying permeable zone D was determined by drastic changes in hydraulic gradients and local lithology of the sediments, as noted previously for other permeable zones.

In Texas, permeable zone E largely coincides with the "Frio" Formation, especially where the permeable zone is overlain by the zone E confining unit (pls. 4, 7). Permeable zone E extends to the land surface in most of Texas, except near the San Marcos arch and Mirando-Provident City fault zone in southern Texas (pl. 2) where the permeable zone begins in the subsurface and consequently does not appear on the map showing outcrops and subcrops of geohydrologic units (pl. 3). The relation of this unit to time-stratigraphic units is shown on plates 7 and 8.

The altitude and configuration of the top of permeable zone E are shown on plate 16. The deepest occurrence is about 10,900 ft below sea level in Brazoria County, Texas, in the Houston embayment, almost 10,000 ft below sea level in the Rio Grande embayment, and more than 10,000 ft below sea level near Lake Charles, Louisiana. The top of the permeable zone is shallowest in southeastern Mississippi and southern Alabama due to increasing distance from the depocenters of the Gulf Coast geosyncline and the effects of the Wiggins anticline and the Hancock arch.

The average thickness of permeable zone E is about 1,400 ft. Maximum thickness is about 4,450 ft in the Rio Grande embayment in southern Texas and almost 3,900 ft near Baton Rouge, Louisiana (pl. 16). The permeable zone is thin far downdip in southeastern Mississippi and southern Alabama, due to the distance from the Gulf Coast geosyncline depocenter and to the effect of the Wiggins anticline and the Hancock arch.

The downdip limit of permeable zone E is the line along which the top of the geopressured zone intersects the top of the permeable zone. The downdip limit of this permeable zone generally remains onshore and occurs near and parallel to the shoreline. The downdip limit is far onshore in a large area in southeastern Louisiana. Thus, this permeable zone is absent in the Terrebonne embayment in southeastern Louisiana. The downdip limit extends slightly offshore in the Rio Grande embayment in southern Texas and extends slightly farther offshore in southeastern Mississippi and southern Alabama.

The farthest updip occurrence of the geopressured zone in this permeable zone (pl. 16) coincides with the downdip limit of the underlying Vicksburg-Jackson confining unit. The top of the geopressured zone forms the base of permeable zone E beyond the downdip limit of the Vicksburg-Jackson confining unit. The geopressured zone is relatively far onshore in the Rio Grande embayment in southern Texas, comes close to the downdip limit of the permeable zone near the shoreline in Nueces and Aransas County, Texas, and remains farther onshore across the rest of Texas to the Texas-Louisiana State line. The geopressured zone extends across the Gulf Coast salt basin in southern Louisiana fairly close to the downdip limit of permeable zone E and then trends slightly offshore in southeastern Mississippi and southern Alabama. The thickness of permeable zone E is truncated from the bottom by the geopressured zone throughout a narrow band near the downdip limit of the permeable zone (pl. 16).

The average sand percentage in permeable zone E is about 40 percent, which is slightly lower than that for permeable zone D. The characteristic coastal band of substantial sand percentages of permeable zone D also is present in permeable zone E. Maximum sand percentages along this band are 40 to 60 percent in Louisiana and Alabama, and 60 to 80 percent in most of Texas and parts of Mississippi (pl. 16). The band is onshore in all areas and is closest to the shoreline in Texas. The band extends farther landward near the Texas-Louisiana State line, extending across the Gulf

Coast salt basin of southern Louisiana, and north of the Terrebonne embayment. The band occurs near the coastline in southern Mississippi and southern Alabama.

Sand percentages in outcrop areas are mostly 20 to 40 percent, but several areas have greater sand percentages. These areas of greater sand percentages extend downdip in a lobate pattern, coalescing in the middip band of maximum sand percentage. A large lobate area exists in southeastern Mississippi and southern Alabama where sand percentages are 60 to 80 percent in the outcrop area. The area extends westward and then downdip to the west of the Wiggins anticline. Another lobe exists in Texas just west of the San Marcos arch. Near these lobes, sand percentages can be less than 20 percent. This characteristic is most pronounced near the lobe west of the San Marcos arch, where large areas with less than 20 percent sand exist, particularly in the area where permeable zone E begins in the subsurface.

Sand percentages decrease downdip of the coastal band due to facies change to clay before permeable zone E is truncated downdip by the geopressured zone. Minimum sand percentages downdip occur in the Gulf Coast salt basin in southern Louisiana where sand percentages generally are less than 20 percent and in places are less than 10 percent. In Texas, where the band of maximum sand percentage is closer to the downdip limit, sand percentages generally are 20 to 40 percent but are 40 to 60 percent in much of the Rio Grande embayment. Sand percentages downdip in southern Mississippi and southern Alabama also decrease to less than 20 percent, mostly due to facies changes to clay but partly due to facies changes to limestone at the eastern boundary of the coastal lowlands aquifer system near Florida.

An anomalous small area of maximum sand percentage occurs in Copiah County, Mississippi. Sand percentages in this area are 60 to 80 percent, whereas percentages in surrounding areas are nearer to 20 percent. A total sand thickness of about 600 ft in this area is also anomalous in relation to nearby areas.

Maximum sand thickness of the permeable zone is more than 3,000 ft in the Rio Grande embayment, coincident with the maximum thickness of the permeable zone and the band of maximum sand percentages. Large areas of thick sand occur along the entire band; sand thickness is almost 1,500 ft on the eastern flank of the Houston embayment and exceeds 1,500 ft in Louisiana. In southeastern Mississippi and southern Alabama, lobate patterns in sand percentages also are reflected in the pattern of total sand thickness.

SUMMARY AND CONCLUSIONS

The coastal lowlands aquifer system, one of three aquifer systems in the Gulf of Mexico sedimentary basin, underlies an area of approximately 160,000 mi^2, including both onshore and offshore areas. The aquifer system is composed predominantly of interbedded sands and clays of Oligocene age and younger. Maximum thickness is more than 18,000 ft in the Terrebonne embayment offshore from southeastern Louisiana, which was the major depocenter, or area of maximum deposition, in the study area. Other areas of major sediment accumulation are the Houston and Rio Grande embayments in Texas. Average thickness of sediments for the entire aquifer system is about 6,000 ft.

The base of the coastal lowlands aquifer system is identified as the top of the massive clay of the Vicksburg-Jackson confining unit. However, because the Gulf Coast RASA study area is restricted to the zone of normal hydrostatic pressure, the base of the aquifer system, in places, is assumed to be the top of the zone of abnormally high fluid pressures (geopressure) where this zone occurs above the sediments making up the Vicksburg-Jackson confining unit. Because the top of the geopressured zone is a discontinuous surface, irregularities exist in the base of the aquifer system and consequently in the total thickness. The coastal lowlands aquifer system was not defined beyond the edge of the Continental Shelf.

Previous investigators divided the sediments of the coastal lowlands aquifer system into various geologic or geohydrologic units or both. The methods used in this report to divide the aquifer system differ from those of previous workers. Two confining units were identified by recognition on bore-hole geophysical logs of a regionally extensive, thick, massive clay interval. Neither of these confining units extends to the land surface, and about 65 percent of the area underlain by the coastal lowlands aquifer system is not underlain by either of the confining units. In areas where confining units do not exist, permeable zones were separated by (1) identification of variations in hydraulic head, usually near pumping centers; (2) extension of permeable-zone boundaries as a constant proportion of the total aquifer system thickness to areas without hydraulic-head data; and (3) minor modification of permeable-zone thickness at locations of bore-hole geophysical logs based on local lithology. The thickness of the permeable zones generally increases with depth where confining units do not exist between them.

The permeable zones are approximately related to time-stratigraphic divisions, although that was not a criterion used in their discretization. In descending order, the geohydrologic units are: permeable zone A (Holocene–upper Pleistocene deposits), permeable zone B (lower Pleistocene–upper Pliocene deposits), permeable zone C (lower Pliocene–upper Miocene deposits), zone D confining unit, permeable zone D (middle Miocene deposits), zone E confining unit, and permeable zone E (lower Miocene–upper Oligocene deposits). The ages of sediments are not everywhere known for the entire aquifer system and in some areas are still disputed. The ages given are the approximate age of the sediments that make up the largest part of a permeable zone. It is recognized that the age of some of the sediments within a particular permeable zone in some areas may not precisely coincide with the age assigned to that zone.

The coastal lowlands aquifer system includes permeable zones whose average thicknesses range from about 700 ft (permeable zone A) to about 2,000 ft (permeable zone C). Maximum thicknesses of the permeable zones range from about 4,450 ft (permeable zone E) to about 7,500 ft (permeable zone D). Zone D and zone E confining units each have an average thickness of about 1,000 ft and maximum thickness of 2,000 ft and 3,300 ft, respectively.

A lobate pattern of coarse-grained sediment accumulation is reflected by the percentages and aggregate thicknesses of sand present in the permeable zones of the coastal lowlands aquifer system. The lobes typically extend from permeable-zone outcrop areas and coalesce in middip areas along a characteristic band of greater sand percentages that approximately parallels the present-day shoreline. The variations in the areal distribution of sand within and among permeable zones indicate horizontal and vertical shifting of facies. The areal distribution of sand in the aquifer system as a whole, however, does not show the extreme variations in sand percentages shown by individual permeable zones. As an example, each individual permeable zone, with the exception of permeable zone E, has at least some areas where sand percentages are greater than 80 percent. If all geohydrologic units are considered together, however, no sand percentages greater than 80 percent are present.

With the exception of permeable zone A, the average sand percentages for each permeable zone fall within a relatively small range, between 40 and 50 percent. The average for the entire aquifer system also is in this range, even though the overall features are more subtle. Permeable zone A has an average sand percentage greater than 60 percent. Because permeable zone A is thin, it has relatively little effect on the average sand percentage for the entire aquifer system. Permeable zone A also is different from the other permeable zones in that the characteristic coastal band of greater sand percentages is absent, and the lobes of greater sand percentages are more prominent. Perhaps this is because this thin zone incorporates sediment deposited during a much shorter time interval than the other permeable zones and does not reflect the persistence of longshore currents existing during the time of deposition. All of the permeable zones, as well as the entire aquifer system, are characterized by a decreasing sand percentage downdip. Because all the permeable zones, with the exception of permeable zone A, are truncated from the bottom by the geopressured zone, successively shallower zones extend farther downdip. Thus, the deepest zone extends the shortest distance downdip from its outcrop, has a smaller area of less than 20 percent sand near its downdip limit, and in some places contains 20 to 40 percent sand at its downdip limit. However, sand percentages in most permeable zones are less than 20 percent at the downdip limit of the zone in offshore areas, especially in those zones that extend to the edge of the Continental Shelf.

SELECTED REFERENCES

Andrews, D.I., 1960, The Louann salt and its relationship to Gulf Coast salt domes: Gulf Coast Association of Geological Societies Transactions, v. 10, p. 215–240.

Baker, E.T., Jr., 1964, Geology and ground-water resources of Hardin County, Texas: Texas Water Commission Bulletin 6406, 179 p.

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

Bear, Jacob, 1979, Hydraulics of groundwater: New York, McGraw-Hill, 569 p.

Bebout, D.G., and Gutierrez, D.R., 1982, Regional cross-sections Louisiana Gulf Coast (western part): Louisiana Geological Survey Folio Series 5, 11 p.

______ 1983, Regional cross-sections Louisiana Gulf Coast (eastern part): Louisiana Geological Survey Folio Series 6, 10 p.

Bennett, G.D., 1979, Regional ground-water systems analysis: Water Spectrum, v. 11, no. 4, p. 36–42.

Bornhauser, Max, 1958, Gulf Coast tectonics: American Association of Petroleum Geologists Bulletin, v. 42, no. 2, p. 339–370.

Bruce, C.H., 1972, Pressured shale and related sediment deformation—A mechanism for development of regional contemporaneous faults: Gulf Coast Association of Geological Societies Transactions, v. 22, p. 23–31.

Carr, J.E., Meyer, W.R., Sandeen, W.M., and McLane, I.R., 1985, Digital models for simulation of ground-water hydrology of the Chicot and Evangeline aquifers along the Gulf Coast of Texas: Texas Department of Water Resources Report 289, 101 p.

Dickinson, George, 1953, Geological aspects of abnormal reservoir pressures in Gulf Coast Louisiana: American Association of Petroleum Geologists Bulletin, v. 37, no. 2, p. 410–432.

Ellisor, A.C., 1944, Anahuac Formation: American Association of Petroleum Geologists Bulletin, v. 28, no. 9, p. 1355–1375.

Fertl, W.H., 1976, Abnormal formation pressures—Developments in petroleum science, 2: New York, Elsevier, 382 p.

Fisk, H.N., 1940, Geology of Avoyelles and Rapides Parishes: Louisiana Department of Conservation Geologic Bulletin 18, 240 p.

Galloway, W.E., 1989, Genetic stratigraphic sequences in basin analysis II. Application to northwest Gulf of Mexico Cenozoic basin: American Association of Petroleum Geologists, v. 73, no. 2, p. 143–154.

Galloway, W.E., Hobday, D. K., and Magara, Kingi, 1982, Frio Formation of the Texas Gulf Coast Basin—Depositional systems, structural framework, and hydrocarbon origin, migration, distribution, and exploration potential: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations 122, 78 p.

Grubb, H.F., 1984, Planning report for the Gulf Coast Regional Aquifer-System Analysis in the Gulf of Mexico Coastal Plain, United States: U.S. Geological Survey Water-Resources Investigations Report 84–4219, 30 p.

Halbouty, M.T., 1979, Salt domes, Gulf Region, United States and Mexico (2d ed.): Houston, Gulf Publishing Company, 561 p.

Harder, A.H., 1960, The geology and ground-water resources of Calcasieu Parish, Louisiana: U.S. Geological Survey Water-Supply Paper 1488, 102 p.

Hosman, R.L., 1988, Geohydrologic framework of the Gulf Coastal Plain: U.S. Geological Survey Hydrologic Investigations Atlas HA–695, scale 1:2,500,000, 2 sheets.

Hosman, R.L., and Weiss, J.S., 1991, Geohydrologic units of the Mississippi embayment and Texas coastal uplands aquifer systems, south-central United States: U.S. Geological Survey Professional Paper 1416–B, 19 p., 19 pl.

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

Jones, P.H., Hendricks, E.L., Irelan, Burdge, and others, 1956, Water resources of southwestern Louisiana: U.S. Geological Survey Water-Supply Paper 1364, 460 p.

Jones, P.H., and Wallace, R.H., Jr., 1974, Hydrogeologic aspects of structural deformation in the northern Gulf of Mexico basin: U.S. Geological Survey Journal of Research, v. 2, no. 5, p. 511–517.

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

Lang, J.W., Winslow, A.G., and White, W.N., 1950, Geology and ground-water resources of the Houston district, Texas: Texas Board of Water Engineers Bulletin 5001, 55 p.

Martin, Angel, Jr., and Whiteman, C.D., Jr., 1985a, Map showing generalized potentiometric surface of aquifers of Pleistocene age, southern Louisiana, 1980: U.S. Geological Survey Water-Resources Investigations Report 84–4331, scale 1:500,000, 1 sheet.

______ 1985b, Map showing generalized potentiometric surface of the Evangeline and equivalent aquifers in Louisiana, 1980: U.S. Geological Survey Water-Resources Investigations Report 84–4359, scale 1:500,000, 1 sheet.

Meyer, R.R., and Turcan, A.N., Jr., 1955, Geology and ground-water resources of the Baton Rouge area, Louisiana: U.S.Geological Survey Water-Supply Paper 1296, 137 p.

Meyer, W.R., and Carr, J.E., 1979, A digital model for simulation of ground-water hydrology in the Houston area, Texas: Texas Department of Water Resources Report LP–103, 27 p.

Neuman, S.P., and Witherspoon, P.A., 1969, Applicability of current theories of flow in leaky aquifers: Water Resources Research, v. 5, no. 4, p. 817–829.

Nyman, D.J., and Fayard, L.D., 1978, Ground-water resources of Tangipahoa and St. Tammany Parishes, southeastern Louisiana: Louisiana Department of Transportation and Development, Office of Public Works Water Resources Technical Report 15, 76 p.

Popkin, B.P., 1971, Ground-water resources of Montgomery County, Texas: Texas Water Development Board Report 136, 131 p.

Rogers, J.E., 1981, Water resources of the Kisatchie well-field area near Alexandria, Louisiana: Louisiana Department of Transportation and Development, Office of Public Works Water Resources Technical Report 26, 57 p.

Rogers, J.E., and Calandro, A.J., 1965, Water resources of Vernon Parish, Louisiana: Louisiana Department of Public Works Water Resources Bulletin 6, 104 p.

Rollo, J.R., 1960, Ground water in Louisiana: Louisiana Department of Public Works Water Resources Bulletin 1, 84 p.

______ 1966, Ground-water resources of the greater New Orleans area, Louisiana: Louisiana Department of Public Works Water Resources Bulletin 9, 69 p.

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

Sampson, R.J., 1978, Surface II graphics system: Kansas Geological Survey, 240 p.

Sandeen, W.M., 1968, Ground-water resources of San Jacinto County, Texas: Texas Water Development Board Report 80, 89 p.

Sandeen, W.M., and Wesselman, J.B., 1973, Ground-water resources of Brazoria County, Texas: Texas Water Development Board Report 163, 199 p.

Torak, L.J., and Whiteman, C.D., Jr., 1982, Applications of digital modeling for evaluating the ground-water resources of the "2,000-foot" sand of the Baton Rouge area, Louisiana: Louisiana Department of Transportation and Development, Office of Public Works Water Resources Technical Report 27, 87 p.

Turcan, A.N., Jr., Wesselman, J.B., and Kilburn, Chabot, 1966, Interstate correlation of aquifers, southwestern Louisiana and southeastern Texas: U. S. Geological Survey Professional Paper 550–D, p. D231–D236.

Wallace, R.H., Jr., Wesselman, J.B., and Kraemer, T.F., 1981, Occurrence of geopressure in northern Gulf of Mexico basin: Conference on Geopressured-Geothermal Energy, Fifth, New Orleans, Louisiana, 1981, scale 1:1,000,000, 1 sheet.

Weiss, J.S., and Williamson, A.K., 1985, Subdivision of thick sedimentary units into layers for simulation of ground-water flow: Ground Water, v. 23, no. 6, p. 767–774.

Wesselman, J.B., 1965, Ground-water resources of Orange County, Texas: Texas Water Commission Bulletin 6516, 112 p.

______ 1967, Ground-water resources of Jasper and Newton Counties, Texas: Texas Water Development Board Report 59, 167 p.

______ 1971, Ground-water resources of Chambers and Jefferson Counties, Texas: Texas Water Development Board Report 133, 173 p.

Whiteman, C.D., Jr., 1979, Saltwater encroachment in the "600-foot" and "1,500-foot" sands of the Baton Rouge area, Louisiana, 1966–78, including a discussion of saltwater in other sands: Louisiana Department of Transportation and Development, Office of Public Works Water Resources Technical Report 19, 49 p.

——— 1980, Measuring local subsidence with extensometers in the Baton Rouge area: Louisiana Department of Transportation and Development, Office of Public Works Water Resources Technical Report 20, 18 p.

Whitfield, M.S., Jr., 1975, Geohydrology of the Jasper and Evangeline aquifers of Southwestern Louisiana: Louisiana Department of Public Works Water Resources Bulletin 20, 72 p.

Wilhelm, Oscar, and Ewing, Maurice, 1972, Geology and history of the Gulf of Mexico: Geological Society of America Bulletin, v. 83, no. 3, p. 575–600.

Williams, T.A., and Williamson, A.K., 1989, Estimating water-table altitudes for regional ground-water flow modeling, U.S. Gulf Coast: Ground Water, v. 27, no. 3, p. 333–340.

Wilson, C.A., 1967, Ground-water resources of Austin and Waller Counties, Texas: Texas Water Development Board Report 68, 219 p.

Wilson, T.A., and Hosman, R.L., 1988, Geophysical well-log data base for the gulf coast aquifer systems, south-central United States: U.S. Geological Survey Open-File Report 87–677, 213 p.

Wood, L.A., and Gabrysch, R.K., 1965, Analog model study of ground water in the Houston district, Texas: Texas Water Commission Bulletin 6508, 103 p.

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