The Geology of North America
Vol. J, The Gulf of Mexico Basin
The Geological Society of America, 1991

Chapter 17

Ground water

John M. Sharp, Jr.
Department of Geological Sciences, The University of Texas at Austin, Austin, Texas 78713-7909
Charles W. Kreitler
Texas Bureau of Economic Geology, The University of Texas at Austin, Austin, Texas 78713
Juan Lesser
Lesser y Asociados, S.A., Seminario 119, Queretaro 76050, Qro., Mexico

INTRODUCTION

Ground water is an important natural resource in the Gulf of Mexico region. Although the region as a whole is relatively rich in water resources, water availability and quality vary dramatically throughout the area. Water resources include rivers—the Chattahoochee, Alabama, Mississippi, Sabine, Trinity, Brazos, Colorado, Rio Grande, and Grijalva—and the immense groundwater resources that are the focus of this chapter. Many major cities in the Gulf of Mexico basin (e.g., Miami, in Florida; Memphis, in Tennessee; Gulfport and Baton Rouge, in Louisiana; and Houston and San Antonio, in Texas) rely chiefly on ground water. Climate varies from moist temperature or subtropical to semiarid conditions, and while population densities (and water-resource demands) vary from minimal to intense, it can be stated that fresh, potable water is the mineral resource in greatest demand. Its continued availability in the region will require special attention in the near future. As elsewhere, the foremost challenge is the provision of adequate quantities of good-quality water, but several special problems exist in the region, including salt-water intrusion and subsidence. An understanding of the hydrogeologic setting of aquifers in the Gulf of Mexico basin is required to preserve and fully utilize this valuable resource.

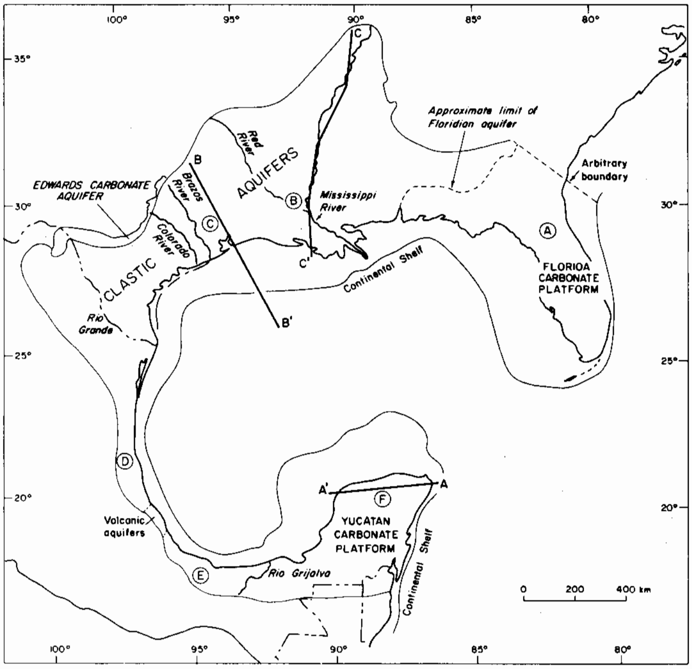

Figure 1. Major aquifers in the Gulf of Mexico basin. Circled letters refer to hydrostratigraphic columns in Table 1.

Aquifers in the Gulf of Mexico basin area (Fig. 1) may be grouped into the following categories: clastic sediments dipping toward the center of the basin; the major carbonate systems of Florida, Texas, and Yucatan; and less importantly, major alluvial aquifers, island aquifers, and volcanic aquifers.

CLASTIC AQUIFERS

The thick section of predominantly Cenozoic clastic sediments is perhaps the chief characteristic of the Gulf of Mexico basin. The sandy units, where part of the meteoric hydrodynamic regime, serve as productive aquifers. Figure 2 is a cross section (B-B′ in Fig. 1) indicating the major features of this section and is adapted from the studies of Fogg and Kreitler (1982), Galloway and others (1982), Wesselman (1983), Donnelly (1988), Grubb and Carrillo R. (1988), Hosman (1988), Pettijohn and others (1988), and Sharp and others (1988). The aquifers are bounded by their outcrop, by lower and, for confined systems, upper clay-rich units, and on occasion, by either geopressures or brackish waters. The major sources of salinity are dissolution of disseminated evaporite minerals within the aquifer, "connate" marine waters, brines migrating upward from the geopressured section, or brines derived from salt-dome dissolution. In most cases, the 10,000 mg/l TDS (total dissolved solids) isocon is shallower than the top of geopressures, but the existence of geopressures is a key

Sharp, J. M., Jr., Kreitler, C. W., and Lesser, J., 1991, Ground water, *in* Salvador, A., ed., The Gulf of Mexico Basin: Boulder, Colorado, Geological Society of America, The Geology of North America, v. J.

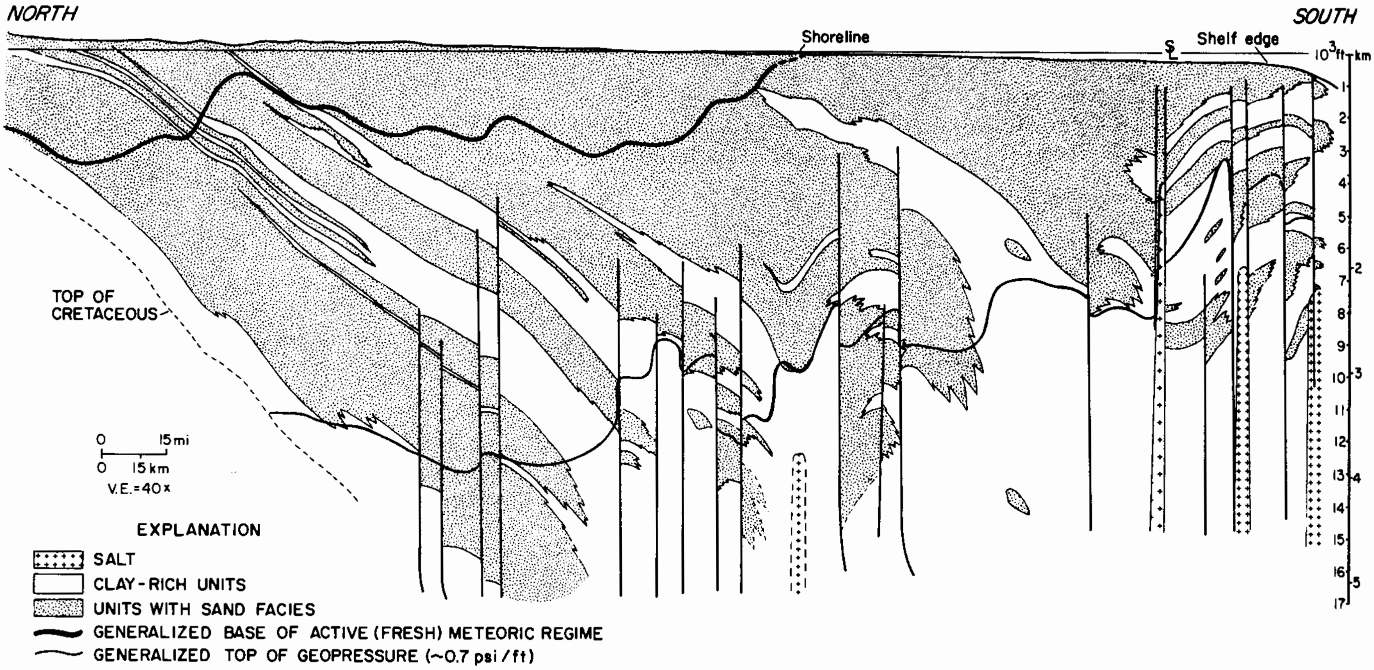

Figure 2. Generalized cross section B-B′ through the northern Gulf Coast clastic section.

element in the clastic units. As demonstrated in a comparison of Figure 2 with Figures 3 and 4, fluid pressures in the meteoric zone are nearly hydrostatic, but at depths of 2 to 4 km the sediments commonly become highly over-pressured.

The geologic evolution of the sediments and sedimentary rocks that make up the aquifers has been treated in detail elsewhere (e.g., Blanchard, 1987; Sharp and others, 1988; Kreitler, 1989; Sharp and McBride, 1989). The sedimentary rocks are exposed to a variety of hydrodynamic systems that leave their imprint on the aquifers. Figure 5 is a flow chart of the possible hydrodynamic systems encountered. The aquifer systems discussed below have been exposed primarily to meteoric water diagenesis. Some have been buried deeply enough to have been altered by deep-burial processes, possibly augmented by free convection.

Generalized hydrostratigraphic columns are given in Table 1. The oldest clastic units of interest are of Cretaceous age. Between Linares and Ciudad Victoria, northwestern Mexico, is a large outcrop of Upper Cretaceous fractured shale. Because of the lack of alternative water resources in the area, this thin section (<50 m) of fractured shale is an important local aquifer. In the upper Mississippi embayment, the Cretaceous McNairy or Ripley Formation is the lowermost important clastic aquifer (Groshkopf, 1955; Brahana and Mesko, 1988), and in central Alabama and adjacent states, the lowermost clastic aquifer is in the sediments of the Cretaceous Tuscaloosa Group (Renken, 1984; Miller and others, 1987).

In most areas of the coastal plain, Cenozoic sandy units are the major aquifers; the shales are not fractured sufficiently to serve as aquifers and serve solely as aquitards. The oldest Cenozoic clastic units of interest are of Paleocene age. During the Paleocene a major transgression created the widespread blanket of clay-rich rocks of the Midway Group. These serve as a confining unit for underlying aquifers throughout the Gulf of Mexico basin. The overlying Paleocene-Eocene Wilcox Group is mostly of nonmarine, fluvial/deltaic origin. Numerous sand lenses of the Wilcox form the lower portions of the Texas Coastal Uplands

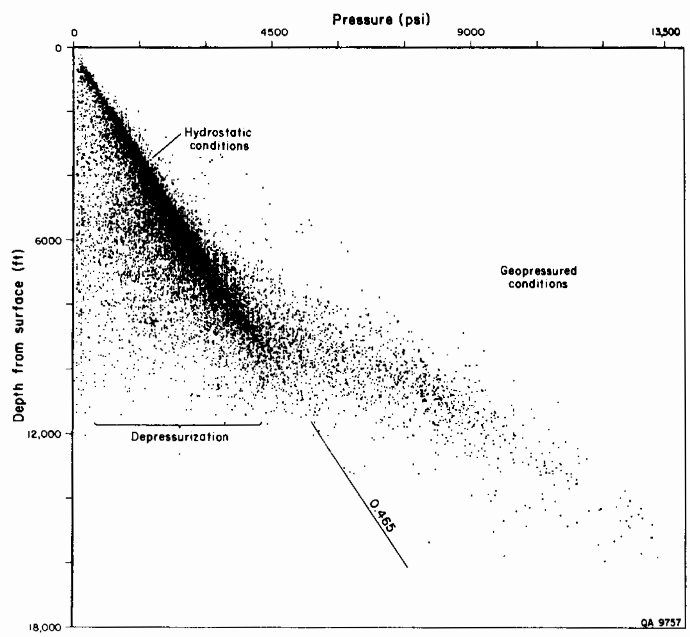

Figure 3. Variation of fluid pressures with depth in the Gulf of Mexico basin in the Texas Frio (Oligocene) Formation (after Kreitler, 1989).

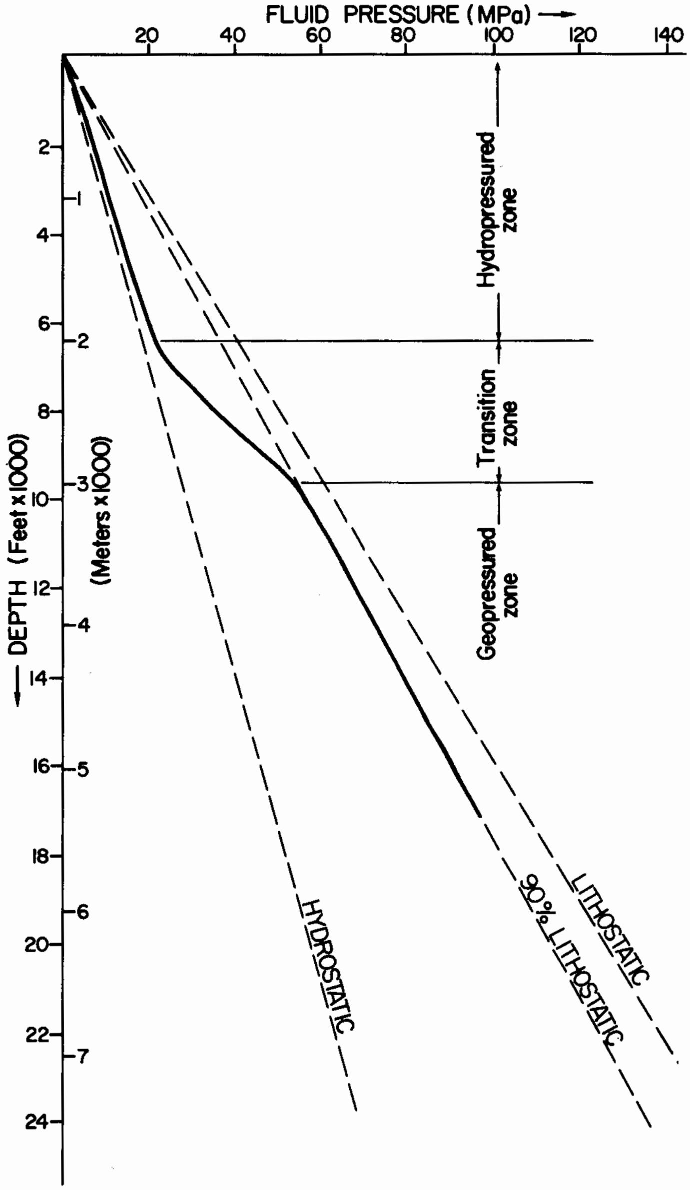

Figure 4. Generalized pattern of fluid pressures for Gulf of Mexico basin sediments (Sharp and others, 1988; reprinted courtesy of Elsevier).

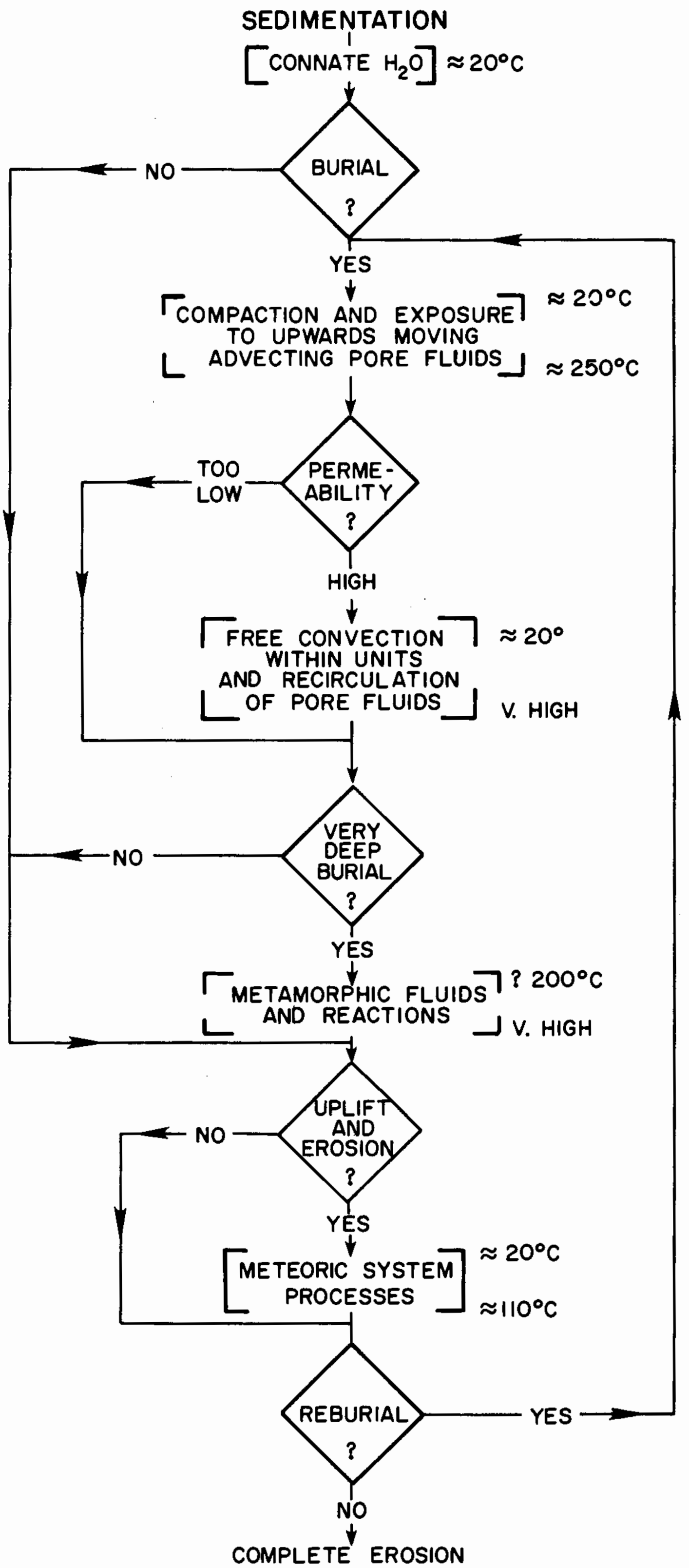

Figure 5. Flow chart of possible hydrodynamic systems to which Gulf Coast aquifers are potentially exposed during their evolution (Sharp and McBride, 1989; reprinted courtesy of Elsevier).

TABLE 1. GENERAL HYDROSTRATIGRAPHIC COLUMNS FOR GULF OF MEXICO CLASTIC UNITS*

		A FLORIDA PENINSULA		B LOUISIANA and MISSISSIPPI EMBAYMENT		C HOUSTON AREA		D TAMPICO-MISANTLA BASIN		E ISTHMUS of TEHUANTEPEC		F YUCATAN PENINSULA	
QUATERNARY	Holocene / Pleistocene	Terraces, surficial sands and phosphorite	Surficial (BISCAYNE) Aquifer	Alluvium and terrace deposits	Chicot Aquifer (Coastal Lowlands Aquifer System)	Alluvium; Beaumont Fm.; Alta Loma Sand; Willis Sand	Upper Chicot Aquifer; Lower Chicot Aquifer (Texas Coastal Lowlands Aquifer System)	Alluvium; Sands and gravels	Surficial Aquifer	Alluvium; Paraje Solo Fm.	Surficial Aquifer; Paraje Solo Aquifer	Alluvium; Limestone and caliche	Yucatan Aquifer Systems
TERTIARY	Pliocene	Undifferentiated deposits	confining bed (hatched)	Citronelle Fm. (Miocene Aquifer System)	Evangeline Aquifer	Goliad Sand	Evangeline Aquifer			Filisola Fm.; Concepción	Filisola Aquifer	Carrillo	
	Miocene	Hawthorn Group; Tampa Ls. Mbr.	Intermediate Aquifer; upper confining unit (hatched); Upper	Fleming Fm.; Catahoula Gp. (Miocene Aquifer System)	Burkeville confining layer (hatched); Jasper Aquifer; Catahoula Ss.	Fleming Fm.; Oakville Ss. Mbr.; Catahoula Ss.	Burkeville confining layer (hatched); Jasper Aquifer; Catahoula Ss.	Tuxpan Fm.; Escolin Fm.	Mostly marine shales and low-permeability sands (hatched)	Encanto Fm.; Deposito Fm.	Mostly marine shales and low-permeability sands (hatched)	Baccalar Fm. (A); Puerto Fm.	
	Oligocene	Suwanee Limestone	Floridan Aquifer	Vicksburg Fm.	(hatched)	Vicksburg Fm. (hatched)	(hatched)	Mesón Fm.; Palma Real Fm.; Horcones Fm.		La Laja Fm.			
	Eocene	Ocala Ls.; Avon Park Ls.; Oldsmar Ls.	Middle confining unit (hatched); Lower Floridan Aquifer	Jackson Group; Claiborne Group; Wilcox Group	Cockfield Fm, A, Sparta Sand, B, Carrizo Sand; Wilcox C Sands (Mississippi Embayment Aquifer System)	Jackson Group (hatched); Claiborne Group; Wilcox Sands	A, Sparta Sand, B, Queen City Sand, C, Carrizo Sand; Wilcox Group (Texas Coastal Uplands Aquifer System)	Chapopote Fm.; Guayabal Fm.; Aragon Fm.		Nanchital Shale		Chichen Itza Fm.	Yucatan Aquifer Systems
	Paleocene	Cedar Keys Ls.	Lower confining unit (hatched)	Midway Group	(hatched)	Midway Group (hatched)	Midway Group (hatched)	Velasco Group				Icaiché Fm.	
CRETACEOUS		Pine Key Ls.		Navarro Group		Navarro Group		Atoyac and Méndez Fms.		Méndez Fm.		Yucatan Fm.	

B: A = Cook Mt. Sh.; B = Cane River Sh. Note: In Mississippi, The Memphis Sand is approx. equivalent to the Sparta Sand; C = Fort Pillow Sand

C: A = Yegua / Cook Mt. Sh.; B = Weches Fm.; C = Reklaw Fm.

F: A: Baccalar Fm. serves as a confining unit in limited areas

*After Turcan and others, 1966; Nyman, 1984; Hosman, 1988; Grubb and Carillo, 1988; Martin and others, 1988; and Scott, 1989.

and Mississippi embayment aquifer systems of Grubb (1984). In south Texas, the Upper Wilcox is an important regional aquifer (Hamlin, 1988). The Wilcox contains many such important aquifers, but the sands, except for the the Fort Pillow sand in the Mississippi embayment, tend to be regionally discontinuous. The overlying Claiborne Group Carrizo Sandstone, which is also nonmarine, contains more regionally extensive sands, as well as more regionally extensive clay layers. The Claiborne forms the upper portion of the Texas Coastal Uplands and Mississippi embayment aquifer systems (Grubb and Carrillo, 1988). The Claiborne's areally extensive sand/sandstone layers, the Cockfield Formation, the Sparta Sand, and the Memphis Sand, are regional aquifers. Farther south, along the coastal plain in northeast Mexico, the Claiborne Group forms a multilayered brackish-water aquifer.

During the late Eocene and Oligocene, a regional transgression deposited the massive marine clays of the Jackson and Vicksburg Groups, which serve as confining layers. Overlying these clays is a thick sequence of Miocene and Pliocene fluvial, deltaic, and shallow-marine deposits—a sequence of alternating, lensoidal, high- and low-permeability units. These are part of the Coastal Lowlands aquifer system in the United States (Grubb, 1984), but do not form significant aquifers along the Mexican portion of the Gulf of Mexico Coastal Plain. The Tertiary section in east-central Mexico is composed mainly of shales; the sands are few and discontinuous. In Texas, locally important units in the Coastal Lowlands aquifer system include the Oakville and Catahoula Sandstones, which also host significant uranium deposits, and the Goliad Sand. Also included in this sequence are the Evangeline and Jasper aquifers of Texas and the Miocene (actually Miocene-Pliocene) aquifer of Louisiana and Mississippi (Hosman, 1988). The Veracruz area is supplied by an alluvial aquifer composed of 100 to 200 m of Tertiary sand and gravel. In the Isthmus of Tehuantepec area of southern Mexico, the Filisola Sand forms an important aquifer near Villahermosa. The Paraje Solo Sand near Veracruz has good potential for future development. Finally, Quaternary alluvial, terrace, and coastal deposits cover the shallowest, coastward portions of the Gulf of Mexico basin. These form important local aquifers onshore and on the barrier islands, and the regionally important Chicot aquifer of the Texas/Louisiana coast. The geologic age of the aquifers generally becomes younger toward the coast, although in some areas, two or more aquifers of different ages are stacked.

Recharge and discharge to these clastic systems correspond to topography. Recharge occurs on the topographic divides, and discharge is generally to the major river systems (Fogg and Kreitler, 1982; Smith and others, 1982; Grubb and Carrillo R., 1988). In the very shallow-dipping, very low-relief regions near the coastline, there is discharge directly to the Gulf of Mexico in bays and lagoons from the shallow unconfined units, and possibly by cross-formational flow from confined aquifers. In general, however, flow is to the river systems (Grubb and Carrillo R., 1988, their Figs. 4, 5, and 6). This limits the amount of flow down the structural dip of these large homoclinal sedimentary packages and also cross-formational flow. Pleistocene sea-level changes may also have had a significant impact on the depth of penetration of fresh ground water. A sea-level drop of approximately 100 m would have caused the shoreline to migrate approximately 320 km gulfward in the northern part of the basin. The continental shelf, which is beneath the Gulf of Mexico, would have been subaerially exposed. The extent of meteoric systems in the Gulf Coastal Plain would have been significantly greater during low sea-level stands, but today the coast generally represents the limit of fresh waters (Kreitler and others, 1977). This indicates rapid flushing of most of the shallow systems, but the degree of flushing of deeper units by meteoric waters remains a controversy (Blanchard, 1987; Bethke, 1989).

The salinity distribution in the clastic aquifers is described in detail by Pettijohn and others (1988), among others. Figure 6 depicts these variations for some of the clastic aquifer units of the northern Gulf of Mexico Coastal Plain, including data for portions of the continental shelf. Low TDS waters occur significantly deeper in the highly transmissive sandstones. The general downflow increase in salinity is evident, as are zones of brines (TDS $\sim 10^5$ mg/l) in many cases, but not in all, which originate by dissolution of salt diapirs (Hanor and others, 1986; Hanor, 1987; Sharp and others, 1988; Kreitler and others, 1989). Major growth faults, however, may limit the coastward extent of fresh ground water (Rollo, 1969; Kreitler, 1977a, b; Kreitler and others, 1977).

Three outcrop maps are shown: the middle Claiborne aquifer (Fig. 7), the mid-Miocene aquifer system (Fig. 8), and upper Pleistocene-Holocene deposits, including the Mississippi River alluvium (Fig. 9).

The middle Claiborne aquifer crops out in a narrow belt near the margin of Tertiary sediments and around the Sabine uplift. Freshwaters (salinities $< 1{,}000$ mg/l) are generally present in the outcrop area and for some distance downdip. In the Mississippi embayment, the freshwater section is areally extensive. The extent of the freshwater section in the middle Claiborne aquifer diminishes southward; south of San Antonio, brackish waters exist even in the outcrop. This is caused by an increase in the amount of shale present and greater aridity. Several local zones of brackish water, one west of the Sabine uplift and one in the Mississippi embayment, represent cross-formational flow, mixing with saline waters leaking from underlying units. The more saline or briny ($> 70{,}000$ mg/l) zones in southern Louisiana represent salt-dome dissolution.

The mid-Miocene aquifer system (Fig. 8) shows similar patterns. The freshwater section is most extensive in Mississippi, Alabama, and Louisiana. Note also the greater extent of the briny facies. The shifting of outcrop and freshwater zones gulfward is the general rule in these clastic units.

Figure 9 depicts the outcrop and salinity zones of upper Pleistocene–Holocene sediments. The freshwater–brackish-water line lies roughly at the coast. It extends slightly gulfward east of New Orleans and inland in south Texas. Again, greater aridity and greater proportions of clay-rich sediment are the probable causes. Salinities of less than mean seawater ($\sim 35{,}000$ mg/l) are

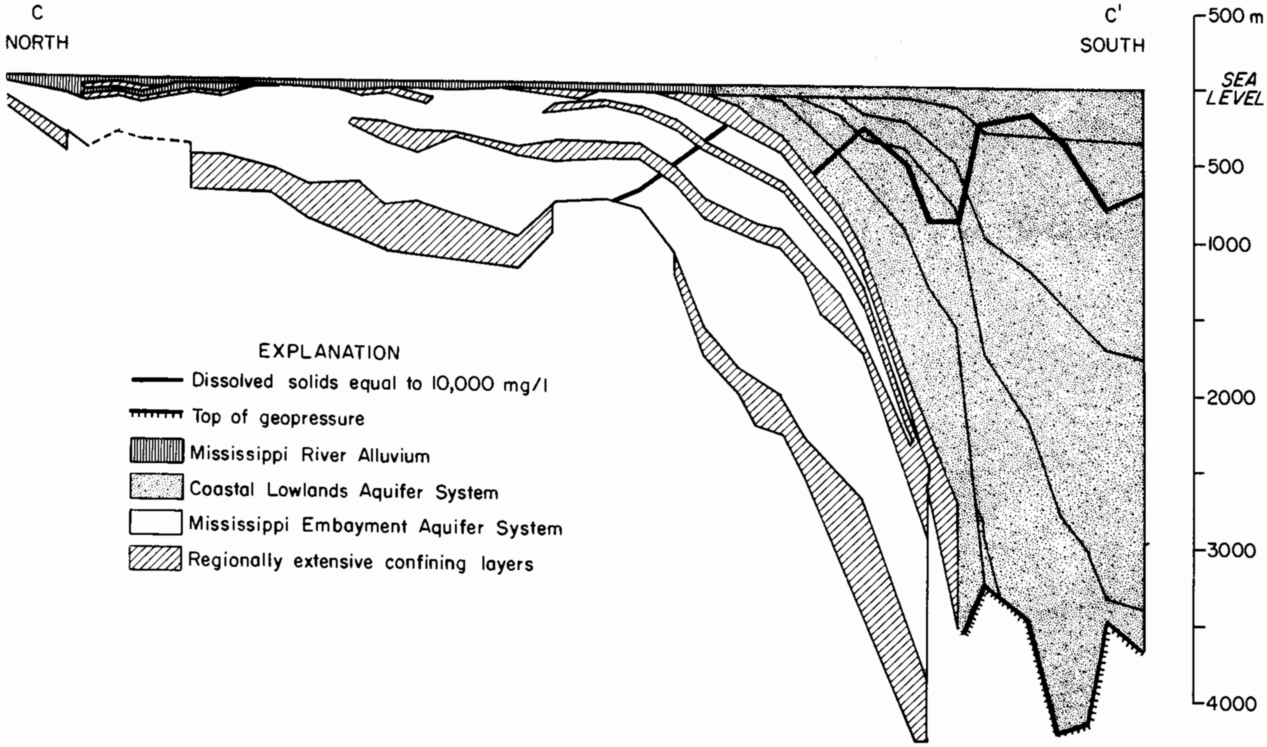

Figure 6. Generalized cross section (C-C′) through the Mississippi embayment (after Grubb and Carillo R., 1988).

not found far offshore from Texas, which indicates the difficulty in flushing saline waters from the system even under greatly lowered sea levels. On the other hand, Pettijohn and others (1988) indicate dissolved solids of less than 35,000 mg/l to the limit of the Louisiana continental shelf, suggesting different conditions perhaps related to the greater rate of Pleistocene sediment deposition in offshore Louisiana. Local areas of brackish waters in the Mississippi embayment represent mixing with ground water from underlying units.

The Coastal Lowland aquifer system (Grubb, 1984) contains geologically young sediments. Grubb and Carrillo R. (1988) extend this unit to the edge of the continental shelf and include all sediments from the land surface of sea floor to the shallower of the top of the Vicksburg-Jackson confining unit or the top of the geopressured zone. The presence of brackish waters in the Beaumont Clay and the thin freshwater section in the Pleistocene of southern Louisiana, and the absence of fresh waters in shallow, confined offshore units, strongly suggest the presence of original ("connate") waters of deposition and inadequate geologic time to flush the "connate" waters.

MAJOR CARBONATE SYSTEMS

Flanking the clastic aquifers of the Cenozoic discussed above are three important carbonate aquifer systems: The Floridan aquifer system, the Edwards (Balcones fault zone) aquifer of Texas, and the Yucatan carbonate aquifer (see Fig. 1). These aquifers are extremely productive and the sole sources of water in their respective areas. The Floridan aquifer supplies the needs of most of Florida (except for the Biscayne aquifer in the greater Miami area); the Yucatan carbonates supply the peninsula and the island of Cozumel. The Edwards aquifer supplies over 2 million people, including the greater San Antonio area, with water.

The *Floridan aquifer system* is a thick (up to 1 km), complex system of Paleocene to Miocene carbonates (Stringfield, 1936; Hanshaw and others, 1965; LeGrand and Stringfield, 1966; Miller, 1986; Johnston and Miller, 1988; Bush and Johnston, 1988; Johnston and Bush, 1988). Four major hydrostratigraphic units are delineated: (1) Lower Eocene and older limestones and clastics that typically contain saline waters; (2) Middle Eocene to Middle Miocene limestones; (3) the confining Hawthorn Group; and (4) the unconfined Quaternary limestones that form the Biscayne aquifer of the Miami area. The Eocene units are the most important hydrogeologically. The aquifer is unconfined along the Florida panhandle, northern Florida, and southern Georgia (Fig. 10). Recharge is abundant in the unconfined and semiconfined areas because of high rainfall (as much as 1,400 mm/yr) and the region's flat topography. Flow is generally from the outcrop and central Florida areas toward the coast. Discharge (mostly via springs) is to several of the large rivers, such as the Suwannee, and by cross-formational flow from confined portions near and even offshore in submerged springs in the Gulf known as "blue holes." The freshwater "lens" of the Floridan aquifer is approximately 600 m (2,000 ft) in north-central Florida, but is very thin in southern Florida.

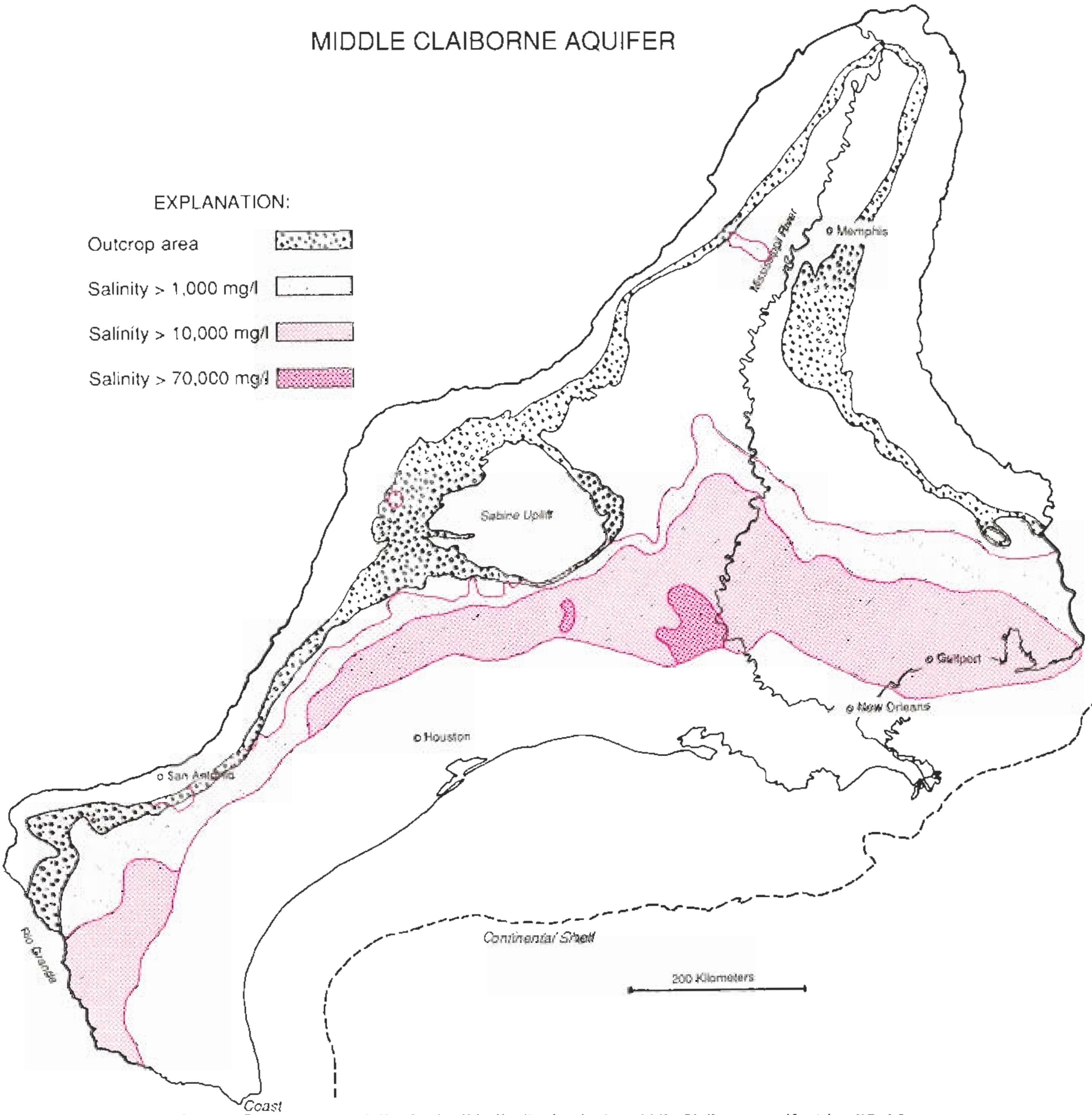

Figure 7. Outcrop area and dissolved solids distribution in the middle Claiborne aquifer (simplified from Pettijohn and others, 1988).

Permeability in the Floridan aquifer is controlled by present and paleokarstification episodes. Dissolution during Miocene and Pleistocene lowstands of sea level created a deep (to 152 m; 500 ft) zone of karstification. In addition, dolomitization, mostly in the freshwater/saltwater mixing area, has both increased and decreased permeability (Thayer and Miller, 1984). Finally, the hydrogeologic effects of the Hawthorn Group must be considered. The Hawthorn limits discharge rates of the underlying units, and thus, depth to the freshwater/saltwater interface in the Floridan aquifer is much deeper than in the Yucatan platform, discussed below. In addition, the greater thickness of the Hawthorn in southern Florida has limited the development of the regional flow system and inhibited karstification of the aquifer. Consequently, the Floridan aquifer is not a significant water resource in south Florida, and the unconfined Biscayne aquifer must be relied upon.

The *Edwards aquifer* (Livingston and others, 1936; Sayre and Bennett, 1942; Woodruff and Abbott, 1979; Maclay and Land, 1988; Sharp, 1990) is found in Cretaceous rocks, deposited on a broad carbonate platform. Miocene-age faulting created a series of down-dropped blocks that control the position of the aquifer (Fig. 11). About 85 percent of the recharge is from ephemeral, losing streams flowing across the outcrop. Flow is generally subparallel to strike, and discharge is via majo springs where the main gulfward-flowing rivers have cut into or through the aquifer (Fig. 12). The southern and eastern boundary of the aquifer is the "bad-water line," the 1,000 mg/l TDS isocon. Unlike the Floridan and Yucatan aquifer systems, where this isocon represents the mixing of fresh water with marine waters, the bad-water line of the Edwards aquifer is formed by three

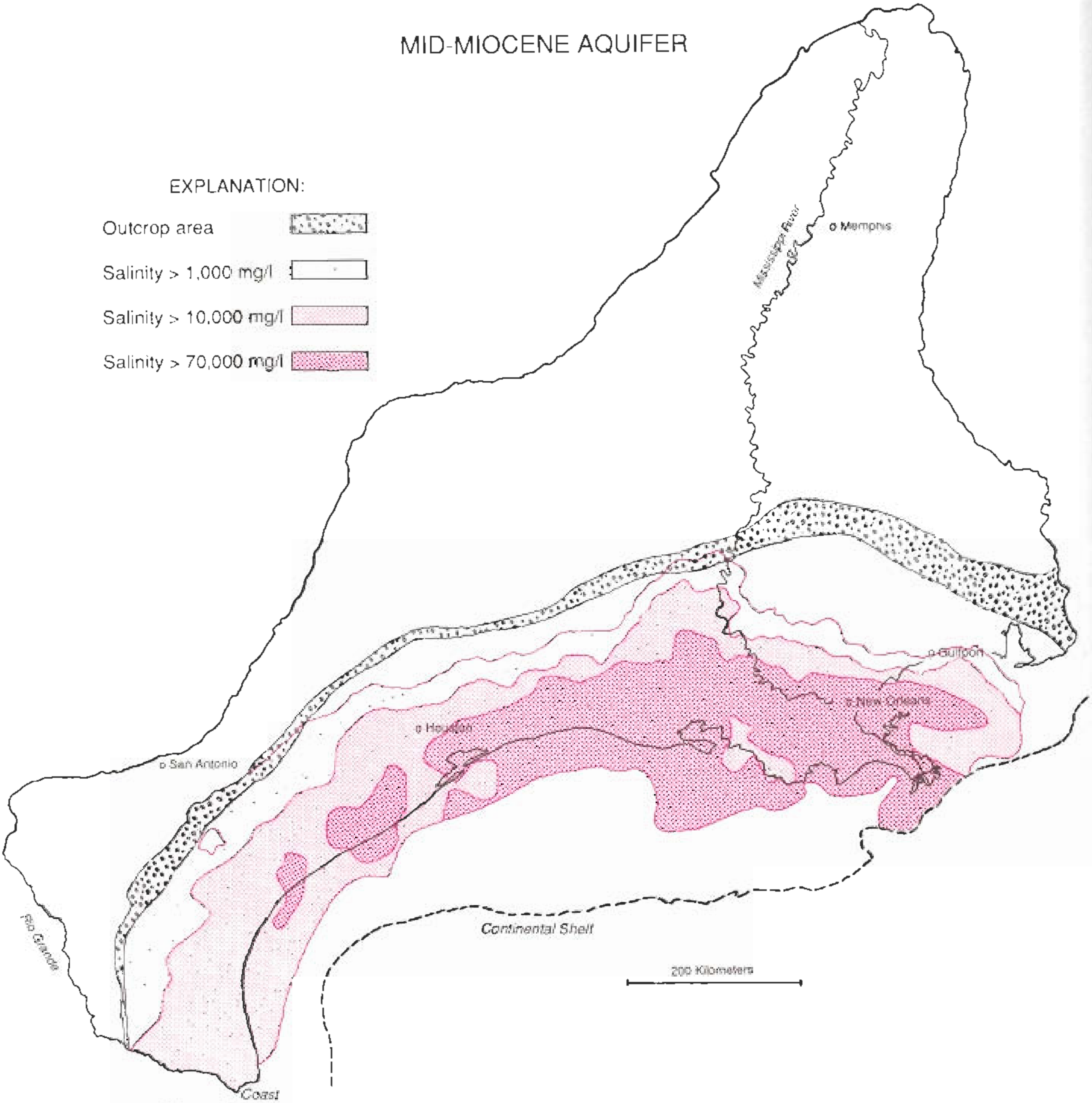

Figure 8. Outcrop area and dissolved solids distribution in the mid-Miocene aquifer system (simplified from Pettijohn and others, 1988).

processes: dissolution of disseminated gypsum and anhydrite (this predominates in the western portions near the Rio Grande); mixing of oil-field like brines from down-dip portions of the Edwards or from underlying units (predominant in the San Antonio–Austin area); and possible cross-formational flow of sulfate-facies water from underlying Cretaceous units, which becomes more important in areas north of Austin, Texas (Sharp and Clement, 1988).

The great permeability of the Edwards aquifer is derived from karstification episodes—one in the Cretaceous and one in the late Cenozoic (late Miocene through Holocene). These episodes effectively leached all halide minerals, selectively dissolved gypsum and anhydrite in evaporite-rich beds and rudistid reef deposits; formed numerous dolines; and enhanced permeability parallel to fault lines.

The *Yucatan Peninsula* possesses an extremely productive

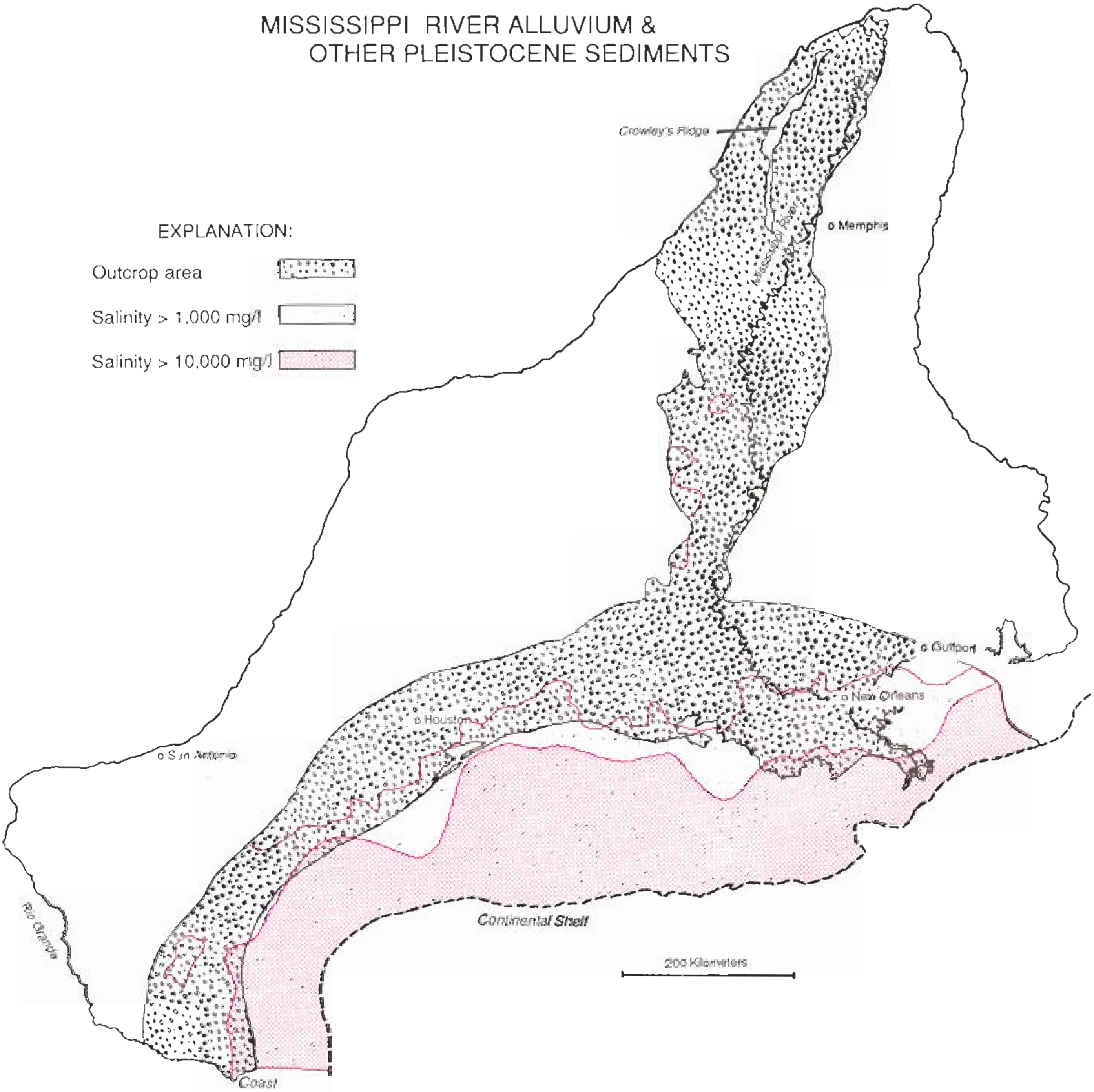

Figure 9. Outcrop area and dissolved solids distribution in the Mississippi River alluvium and other Pleistocene sediments (simplified from Pettijohn and others, 1988).

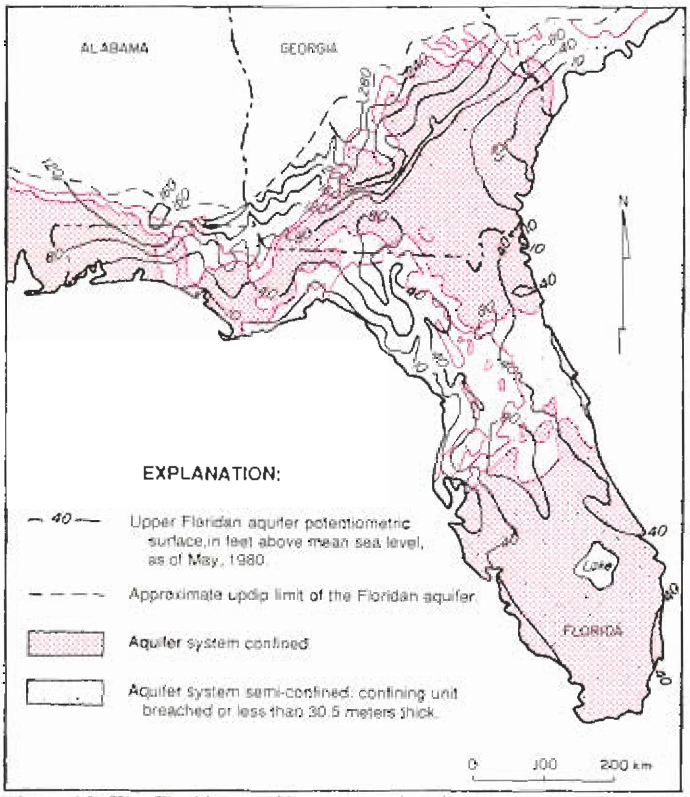

Figure 10. The Floridan aquifer system, showing areas of confinement and semiconfinement. Generalized equipotentials are also depicted (after Johnston and Miller, 1988).

aquifer system (Lesser, 1976; Lesser and others, 1978; Back and Lesser, 1981; Marin and others, 1990). The peninsula is generally situated at less than 50 m above sea level in a humid tropical climate (800 to 1,700 mm/yr precipitation), but there is both a wet and a dry season. The Tertiary carbonates possess a maximum thickness of about 1,000 m (Lesser and Weidie, 1988) and overlie Cretaceous carbonates and evaporites. The major aquifers are developed in Eocene or Miocene/Pliocene units. In many respects, the Yucatan carbonates are similar to those in Florida, but the low relief and the absence of significant confining layers have led to a vastly different hydrogeologic setting.

The exposed carbonates are subject to intense chemical weathering, which leads to the formation of the cenotes (vertical limestone shafts, open to the surface, which contain standing water), collapsed bays (caletas) along the coasts, elongated depressions along fault trends, and the formation of tropical soils. Rainwater enters the aquifer still unsaturated with respect to calcite. In the eastern Yucatan, coastal geomorphology is controlled by fracture trends and calcite dissolution, which results from the mixing of meteoric and marine waters (Back and others, 1979). No confining layers are present, unlike in Florida. The aquifer is therefore extremely permeable. Heads in the aquifer vary from only a few meters in the central part of the Peninsula to a few centimeters above sea level near the coast (Fig. 13), where the freshwater aquifer is relatively thin because of both the very high transmissivity and sea-water intrusion. At Chichén Itzá, for example, 80 km from the coast, the land surface and the water table are at elevations of 30 and 1.2 m above sea level, respectively. The lens of fresh water, up to several tens of meters thick, thins toward the coast (Fig. 14). Salinity is controlled by sea-water intrusion on a massive scale and dissolution of evaporite minerals. The intrusion occurs cyclically. During the dry season, the freshwater/saltwater interface moves inland from 100 m to as much as 12 km in Dzidzantun (north-central part of Yucatan; Lesser and Weidie, 1988) because of high pumping, lack of re-

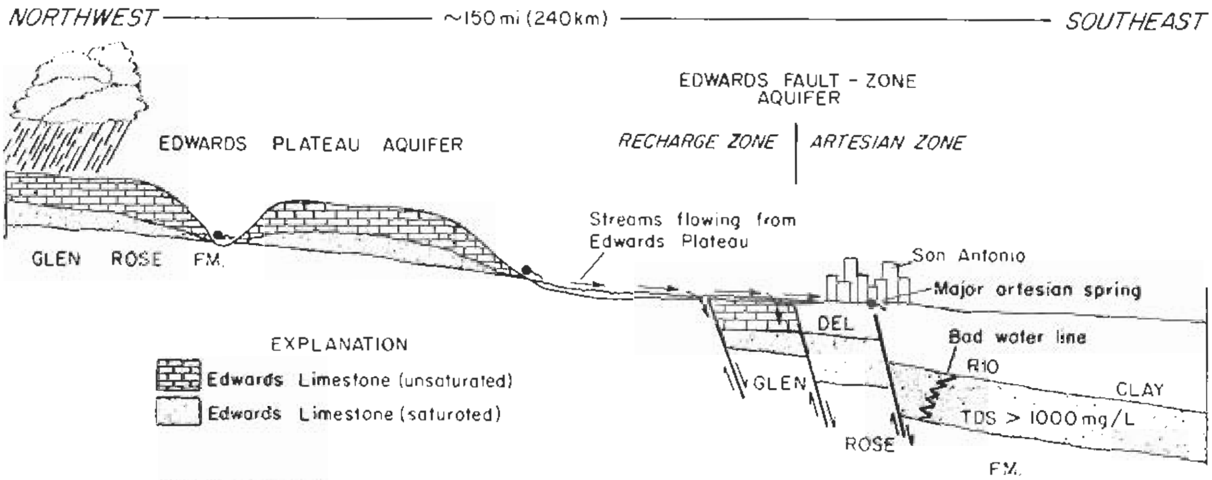

Figure 11. Cross section through the Edwards aquifer, depicting fault controls of aquifer geometry (from Clement and Sharp, 1988; reprinted courtesy of the National Water Well Association, Dublin, Ohio).

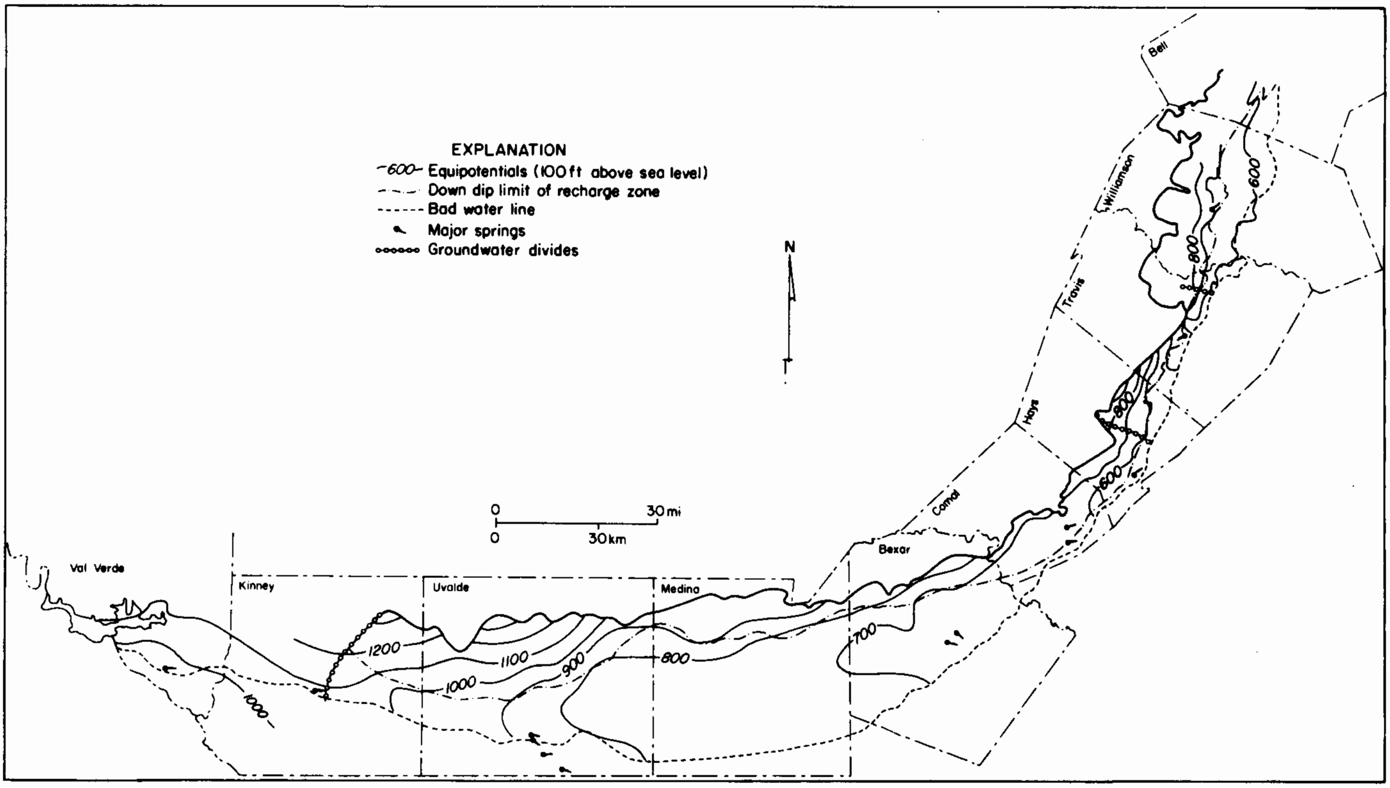

Figure 12. Edwards aquifer's confined and unconfined areas and major springs. Also shown is the bad-water line (Clement and Sharp, 1988; reprinted courtesy of the National Water Well Association, Dublin, Ohio).

charge, high permeability, and lack of effective storage in the carbonates. During the rainy season, the interface moves coastward. The drops of sea level during Pleistocene and earlier low sea-level stands, and therefore drops in the regional base level, have probably been a major control on developing the very high permeabilities observed in both the Floridan and Yucatan carbonate aquifers.

QUATERNARY ALLUVIAL AQUIFERS

The large rivers flowing through the Gulf Coastal Plain are commonly associated with thick bands of alluvium (Rosenshein, 1988; Sharp, 1988). The flood-plain alluvial systems are very important water resources (Ackerman, 1989). The most important alluvial system in terms of potential production is associated with the Mississippi River. The Mississippi River alluvium consists of several hundred meters of clastic sediment deposited during the late Pleistocene (Fisk, 1944; Boswell and others, 1968; Sharp, 1988). Thick top-stratum clays create a significant confined aquifer in western Mississippi; in other sites, the aquifer is unconfined. The Brazos, Red, and Colorado Rivers also form important but local aquifers.

Water quality in alluvial systems, although hard, is generally suitable for most uses. Iron, above drinking-water standards, is occasionally present, and in some areas, salinities become high

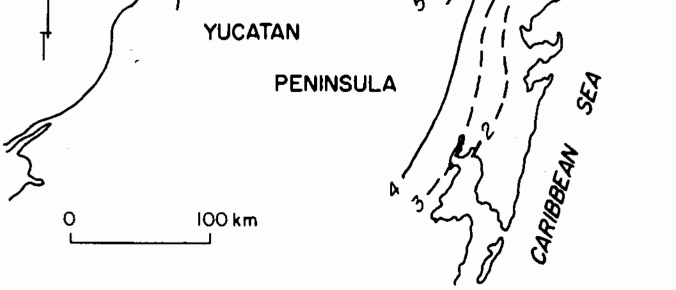

Figure 13. Water-table elevations in the Yucatan Peninsula (after Lesser and Weidie, 1988).

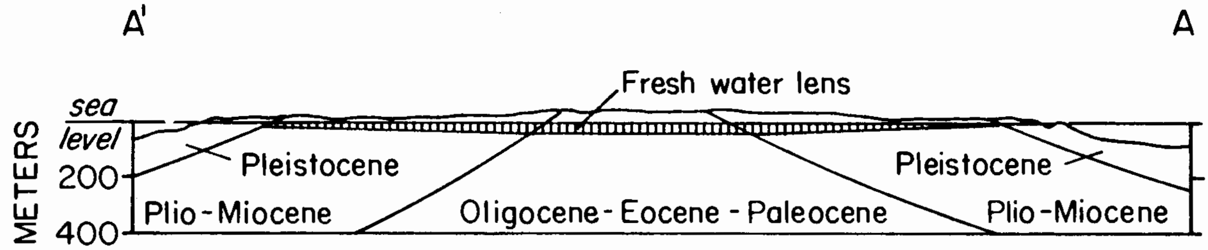

Figure 14. Cross section (A-A′) through the Yucatan Peninsula, showing the thin freshwater lens (after Back and Hanshaw, 1970).

because of significant flow from adjoining clastic units. The sediments in these alluvial aquifers reflect the paleodepositional controls of varying sea level and stream discharge during the Pleistocene. The rivers tend to be underfit, and the most productive, coarsest sediment is often found in the substratum near the base of the alluvial fill.

OTHER AQUIFERS

In east-central Mexico, Pliocene-age basalt flows and alluvial-valley sediments are the major ground-water providers (Grubb and Carrillo R., 1988). The basalt flows cover several thousand square kilometers and are several tens of meters thick. The alluvial systems cut across these basalt flows. The alluvium may be several tens of meters thick.

On the barrier islands that parallel much of the northwestern and northern coast of the Gulf of Mexico, freshwater lenses are important local aquifers. Well-sorted beach sands provide aquifers with saturated thicknesses of up to tens of meters overlying saline water. Highly permeable limestones, such as the Island of Cozumel, have much thinner lenses. Consequently, moderate (10^{-2} to 10^{-4} cm/sec) hydraulic conductivity sediments provide the best aquifers. Water on the islands is limited because of the potential for salt-water intrusion and the thin freshwater lenses, but the water is typically of good quality.

CRITICAL PROBLEMS

While the ground-water resources of the Gulf of Mexico basin are vast, there are, as alluded to above, significant problems, both existing and future. These include water availability, natural water quality, pollution, subsidence, and potential rising sea levels.

Water availability

Where surface-water resources are not available, ground water can be relied upon in the Gulf of Mexico basin, except where thick, clayey units are present at the surface. These clayey units include some Upper Cretaceous units (such as the Navarro and Taylor Formations of central Texas), the Midway Group, the Jackson Group, the Vicksburg Group, Eocene to Miocene units in the northeastern Mexican coastal plain, and some Pleistocene clays. Even in the thick confining units, however, thin, discontinuous lenses of permeable sands are generally present so that water availability often is dependent upon quality considerations. Growth faults serve to truncate some units and limit the extent of some aquifers. High permeabilities are formed by dissolution along fault surfaces in carbonate units. Nevertheless, with the exception of the Edwards aquifer, structural controls are generally less important than stratigraphic controls.

Natural water quality

Because of the vicinity of the Gulf of Mexico (aerosols in the form of salt crystals), the dissolution of salt domes and disseminated evaporite minerals, the abundance of young marine and young coastal sediments with saline/brackish pore fluids, and perhaps, the mixing with migrated oil-field waters (including brines), water salinity is a major quality problem. In organic-rich sediments, reducing conditions generate abundant dissolved iron and organic constituents that can be a problem.

Heavy pumping of coastal aquifers has caused salt-water intrusion in clastic and, more significantly, in the highly permeable carbonate systems. This, coupled with subsidence risks, has caused many coastal municipalities to switch to surface-water resources where possible.

Pollution

Aquifer systems of the Gulf of Mexico basin are highly susceptible to contamination. This is especially demonstrated in the Yucatan Peninsula, where sewage treatment plants are rare. Consequently, municipal, industrial, agricultural, and domestic wastes rapidly enter the highly permeable limestones because soils are thin and numerous karst features extend to the surface. There is little sorption or retention of contaminants, which are readily transported in fractures. Fecal coliform bacteria can survive for several years in warm, Yucatan Peninsula ground waters; enteritis and other intestinal diseases were a factor in over 50 percent of the deaths in the area (Doehring and Butler, 1974), and the Mexican government is engaged in a massive campaign to provide safe municipal and rural water supplies. The geologic situation is similar in the Edwards and Floridan aquifers, but pollution is less today because significant portions of these aquifers are confined and because there are more and better waste treatment facilities. In the Edwards aquifer system, considerable efforts are being made to control the quality in the streams that naturally recharge the aquifer. Such control of recharge is less feasible in the Florida and Yucatan Peninsulas because of the large areal extent of their recharge zones.

The clastic sedimentary aquifers have a high potential for contamination because of industrial development along the Gulf of Mexico Coastal Plain. Numerous industrial-waste disposal sites are present at the land surface, which provide potential point sources of pollution. The greater Houston area has a large number of such sites from previous improper chemical-waste disposal; there are numerous other sites throughout the Gulf of Mexico basin. An alternative method of disposal of hazardous chemicals is by deep injection into saline, clastic formations in Louisiana and Texas (Kreitler and others, 1989). Texas alone has over 100 industrial waste-injection wells, which inject more than 6 billion gallons of liquid hazardous wastes each year. Leaks in poorly constructed or failed injection or petroleum-production wells and underground storage tanks have caused aquifer pollution in both Mexico and the United States. Finally, Texas and Louisiana have potentially significant air pollution. Aerosols may be causing low levels of widespread but significant aquifer contamination (Brown and Sharp, 1989).

Subsidence

The extraction of subsurface fluids has created severe subsidence along the Texas and Louisiana coasts (Gabrysch, 1982, 1984). More than 2 m of subsidence has occurred in the greater Houston area since the mid-1940s, primarily because of ground-water pumping. Other areas of notable subsidence include northeast of Corpus Christi, Texas. In these areas, surface-water resources have been sought. Unfortunately, reservoirs trap sediment and reduce sediment input to the Gulf. This is causing still-unknown changes in coastal geomorphology and may accelerate the general coastline retreat. Subsidence has caused the submergence of roads, houses, and port facilities, and differential subsidence has caused or accelerated fault movement and, thus, disrupted roads and utilities systems. In the Yucatan Peninsula, but more importantly in Florida, pumping has led to catastrophic sinkhole collapses (Beck, 1984). Identification of potential areas of sinkhole collapse is extremely difficult and thus exacerbates a very dangerous problem.

Finally, high rates of local subsidence have been traced to petroleum production (Pratt and Johnson, 1926; Kreitler, 1977b; and Holzer and Bluntzer, 1984). The more regional subsidence observed in the upper Texas coast has been also attributed to depressurization of petroleum reservoirs (Ewing, 1985; Germiat and Sharp, 1990; Sharp and Germiat, 1990).

Rising sea levels

The general historical retreat of the Gulf of Mexico shoreline is accelerated by subsidence and may be further accelerated by future eustatic sea-level rise. Gornitz and Lebedeff (1987) suggest a worldwide rate of sea-level rise of approximately 1.5 mm/yr. Tidal gauges along the Florida Gulf Coast show a higher rate (2.2 to 2.4 mm/yr) since 1908. Sharp and Germiat (1990) attribute this to downwarping of the crust by the thick pile of Cenozoic sediment. Eustatic sea-level rises of as much as 5 m by 2100 have been predicted. Sharp and Germiat's delphic analysis suggests a 50 percent chance for a rise of more than 1 m by 2100. The projections indicate that the Gulf of Mexico coastal areas will experience exacerbated shoreline retreat and inundation of wetlands in the next century. These will have drastic hydrogeologic, economic, and societal impacts.

CONCLUSIONS

The availability of ground water in the Gulf of Mexico basin has been and will continue to be critical in the social and economic development of this region by providing water for agriculture, industry, and small and large municipalities. Abundant supplies have been found predominantly in the Mesozoic to Cenozoic limestones and Cenozoic sandstones.

The best limestone aquifer is the Floridan aquifer, because of its high transmissivities and rapid, abundant recharge. It has a potential for additional production, but increased development over the aquifer may result in its contamination. Future ground-water production of the Edwards aquifer in Texas is more limited because of the drier climate, lower rates of recharge, its less extensive recharge area, potential overdevelopment, and environmental concerns. Farmers, municipalities, river authorities, and environmentalists are already fighting over the water rights for the aquifer. Future ground-water production from limestone aquifers of the Yucatan limestones will be limited by the thin freshwater lens.

Sand and sandstone aquifers in the Gulf of Mexico basin region are areally extensive and provide water supplies for major cities, small communities, industry, and agriculture. Ground water from Tertiary sandstones will continue to provide a major percentage of water for these users. Much of this production is mining water thousands of years old from confined aquifers, but the resource is vast. The potential for surface contamination of confined aquifers is minor, but the shallow unconfined portions of the systems are susceptible. Differential land subsidence, inundation, and saltwater intrusion require careful utilization of these water supplies. Inundation and intrusion, however, are coastal problems; future development may require new sites that are further inland.

REFERENCES CITED

Ackerman, J. D., 1989, Hydrology of the Mississippi River valley alluvial aquifer, south-central United States: U.S. Geological Survey Water-Resources Investigations Report 88-4028, 74 p.

Back, W., and Hanshaw, B. B., 1970, Comparison of chemical hydrogeology of the carbonate peninsulas of Florida and Yucatan: Journal of Hydrology, v. 10, p. 330–368.

Back, W., and Lesser, J. M., 1981, Chemical constraints on groundwater management in the Yucatan Peninsula, Mexico, *in* Beard, L. R., ed., Water for survival: Journal of Hydrology, v. 51, p. 119–130.

Back, W., Hanshaw, B. B., Pyle, T. E., Plummer, N., and Weidie, A. E., 1979, Geochemical significance of groundwater discharge and carbonate solution to the formation of Caleta Xel Ha, Quintana Roo, Mexico: Water Resources Research, v. 15, no. 6, p. 1521–1535.

Beck, B. F., ed., 1984, Sinkholes; Their geology, engineering, and environmental impact: Boston, Massachusetts, A. A. Balkema, 429 p.

Bethke, C. M., 1989, Modeling subsurface flow in sedimentary basins: Geologische Rundschau, v. 78, p. 129–154.

Blanchard, P. E., 1987, Fluid flow in compacting sedimentary basins [Ph.D. thesis]: Austin, University of Texas, 190 p.

Boswell, E. H., Cushing, E. M., and Hosman, R. L., 1968, Quaternary aquifers of the Mississippi Embayment: U.S. Geological Survey Professional Paper 448-E, 29 p.

Brahana, J. V., and Mesko, T. O., 1988, Hydrogeology and preliminary assessment of regional ground-water flow in the Upper Cretaceous and adjacent aquifers, northern Mississippi Embayment: U.S. Geological Survey Water-Resources Investigations Report 87-4000, 65 p.

Brown, T. J., and Sharp, J. M., Jr., 1989, Modeling the effect of aerosol dispersal on ground-water systems: Geological Society of America Abstracts with Programs, v. 21, p. 496.

Bush, P. W., and Johnson, R. H., 1988, Ground-water hydraulics, regional flow, and ground-water development of the Floridan aquifer system in Florida, and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paepr 1403-C, 80 p.

Clement, T. J., and Sharp, J. M., Jr., 1988, Hydrochemical facies in the bad-water zone of the Edwards aquifer, central Texas, *in* Proceedings of the Ground Water Geochemistry Conference: Dublin, Ohio, National Water Well Association, p. 127–149.

Doehring, D. O., and Butler, J. H., 1974, Hydrogeologic constraints on Yucatan's development: Science, v. 186, p. 591–595.

Donnelly, A.C.A., 1988, Meteoric water penetration in the Frio Formation, Texas Gulf Coast [M.A. thesis]: Austin, University of Texas, 137 p.

Ewing, T. E., 1985, Subsidence and surface faulting in the Houston-Galveston area, Texas–related to deep fluid withdrawal?, *in* Dorfman, M. H., and Morton, R. A., eds., Geopressured-geothermal energy: Austin, Texas, University of Texas, Proceedings of the 6th U.S. Gulf Coast Geopressured-Geothermal Energy Conference, p. 289–298.

Fisk, H. N., 1944, Geological investigation of the alluvial valley of the lower Mississippi River: U.S. Army Corps of Engineers Mississippi River Commission, 78 p.

Fogg, G. E., and Kreitler, C. W., 1982, Ground-water hydraulics and hydrochemical facies in Eocene aquifers of the East Texas Basin: Texas Bureau of Economic Geology Report of Investigation 127, 75 p.

Gabrysch, R. K., 1982, Groundwater withdrawals and land surface subsidence in the Houston-Galveston region, Texas, 1906–1980: U.S. Geological Survey Open-File Report 72-571, 68 p.

——, 1984, Case history 9.12; The Houston-Galveston region, Texas, U.S.A., *in* Poland, J. F., ed., Guidebook to studies of land subsidence due to groundwater withdrawal: Paris, UNESCO, p. 253–262.

Galloway, W. E., Hobday, D. K., and Magara, K., 1982, Frio Formation of the Texas Gulf Coast basin; Depositional systems, structural framework, and hydrocarbon origin, migration, distribution, and exploration potential: Texas Bureau of Economic Geology Report of Investigation 122, 78 p.

Germiat, S. J., and Sharp, J. M., Jr., 1990, Assessment of future coastal land loss along the upper Texas Gulf coast: Bulletin of the Association of Engineering Geologists, v. 19 (in press).

Gornitz, V., and Lebedeff, S., 1987, Global sea-level changes during the past century, *in* Nummedal, D., and others, eds., Sea-level fluctuations and coastal evolution: Society of Economic Paleontologists and Mineralogists Special Publication 41, p. 3–16.

Groshkopf, J. G., 1955 , Subsurface geology of the Mississippi Embayment of southeast Missouri: Missouri Division of the Geological Survey and Water Resources, v. 37, 2nd series, 133 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.

Grubb, H. F., and Carrillo R., J. J., 1988, Region 23, Gulf of Mexico Coastal Plain, *in* Back, W., Rosenshein, J. S., and Seaber, P. R., eds., Hydrogeology: Boulder, Colorado, Geological Society of America, The Geology of North America, v. O-2, p. 219–228.

Hamlin, H. S., 1988, Depositional and ground-water flow systems of the Carrizo–upper Wilcox, southern Texas: Texas Bureau of Economic Geology Report of Investigation 175, 61 p.

Hanor, J. S., 1987, Kilometer-scale thermohaline overturn of pore waters in the Louisiana Gulf Coast: Nature, v. 327, p. 501–503.

Hanor, J. S., Bailey, J. E., Rogers, M. C., and Milner, L. R., 1986, Regional variations in physical and chemical properties of south Louisiana oil field brines: Transactions of the Gulf Coast Association of Geological Societies, v. 36, p. 143–149.

Hanshaw, B. B., Back, W., and Rubin, M., 1965, Carbonate equilibrium and radiocarbon distribution related to groundwater flow in the Floridan limestone aquifer, U.S.A., *in* Hydrology of fractured rocks, vol. 1: UNESCO, International Association of Scientific Hydrology, p. 601–614.

Holzer, T. L., and Bluntzer, R. L., 1984, Land subsidence near oil and gas fields, Houston, Texas: Ground Water, v. 22, p. 450–459.

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

Johnson, R. H., and Bush, P. W., 1988, Summary of the hydrology of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403-A, 24 p.

Johnston, R. H., and Miller, J. A., 1988, Region 24, Southeastern United States, *in* Back, W., Rosenshein, J. S., and Seaber, P. R., eds., Hydrogeology: Boulder, Colorado, Geological Society of America, The Geology of North America, v. O-2, p. 229–236.

Kreitler, C. W., 1977a, Fault control of subsidence, Houston-Galveston, Texas: Ground Water, v. 15, no. 3, p. 203–214.

——, 1977b, Faulting and land subsidence from groundwater and hydrocarbon production, Houston-Galveston, Texas, *in* 2nd International Land Subsidence Symposium Proceedings, Anaheim, California, 1976: International Association of Hydrological Sciences Publication 121, p. 435–445.

——, 1989, Hydrogeology of sedimentary basins: Journal of Hydrology, v. 106, p. 29–53.

Kreitler, C. W., Guevera, E., Granata, G., and McKalips, D., 1977, Hydrogeology of Gulf Coast aquifers, Houston-Galveston area, Texas: Transactions of the Gulf Coast Association of Geological Societies, v. 27, p. 72–89.

Kreitler, C. W., Akhter, M. S., and Donnelly, A.C.A., 1989, Hydrologic-hydrochemical characterization of Texas Gulf Coast saline formations used for deep-well injection of chemical wastes, *in* Proceedings of the International Symposium on Class I and II Injection Wells: Underground Injection Practice Research Foundation, p. 177–197.

LeGrand, H. E., and Stringfield, V. T., 1966, Development of permeability and storage in the Tertiary limestones of the southeastern states, USA: International Association of Scientific Hydrology Bulletin, v. 11, p. 61–73.

Lesser, H., Azpeitia, J., and Lesser, J. M., 1978, Geohidrología de la Isla de

Cozumel, Quintana Roo: Recursos hidráulicos, v. VII, no. 1, 18 p.
Lesser, J. M., 1976, Bosquejo geológico e hidrogeoquímico de la Península de Yucatán: Secretaría de Recursos Hidráulicos Boletín, no. 10, June, 11 p.
Lesser, J. M., and Weidie, A. E., 1988, Region 25, Yucatan Peninsula, *in* Back, W., Rosenshein, J. S., and Seaber, P. R., eds., Hydrogeology: Boulder, Colorado, Geological Society of America, The Geology of North America, v. O-2, p. 237–241.
Livingston, P., Sayre, A. N., and White, W. N., 1936, Water resources of the Edwards Limestone in the San Antonio area, Texas: U.S. Geological Survey Water-Supply Paper 773-B, 55 p.
Maclay, R. W., and Land, L. F., 1988, Simulation of flow in the Edwards aquifer, San Antonio region, Texas, and refinement of storage and flow concepts: U.S. Geological Survey Water-Supply Paper 2336, 48 p.
Marin, L. E., and 5 others, 1990, Hurricane Gilbert; Its effects on the aquifer in northern Yucatan, Mexico, *in* Simpson, E. S., and Sharp, J. M., Jr., eds., Selected Papers on Hydrogeology: Heise, Hannover International Association of Hydrogeologists, v. 1, p. 111–127.
Martin, A., Jr., Whiteman, C. D., Jr., and Becnel, M. J., 1988, Generalized potentiometric surface of the upper Jasper and equivalent aquifers in Louisiana, 1984: U.S. Geological Survey Water-Resources Investigations Report 87-4139, 2 sheets, scale 1:500,000.
Miller, J. A., 1986, Hydrogeologic framework of the Floridan aquifer system in Florida and in parts of Georgia, Alabama, and South Carolina: U.S. Geological Survey Professional Paper 1403-B, 91 p.
Miller, J. A., Barker, R. A., and Renken, R. A., 1987, Hydrology of the southeastern Coastal Plain aquifer system; An overview, *in* Vecchioli, J., and Johnson, A. I., eds., Aquifers of the Atlantic and Gulf Coastal Plain: American Water Resources Association Monograph 9, p. 53–77.
Nyman, D. J., 1984, The occurrence of high concentrations of chloride in the Chicot aquifer system of southwestern Louisiana: Louisiana Department of Transportation and Development Office of Public Works, Water Resources Technical Report 33, 75 p.
Pettijohn, R. A., Weiss, J. S., and Williamson, A. K., 1988, Distribution of dissolved-solids concentrations and temperature in ground water of the Gulf Coast aquifer systems, south-central United States: U.S. Geological Survey Water-Resources Investigations Report 88-4082, 5 sheets.
Pratt, W. E., and Johnston, D. W., 1926, Local subsidence of the Goose Creek oil field: Journal of Geology, v. 34, p. 577–590.
Renken, R. A., 1984, The hydrogeologic framework of the southeastern Coastal Plain aquifer system of the United States: U.S. Geological Survey Water-Resources Investigations Report 84-4243, 26 p.
Rollo, J. R., 1969, Salt-water encroachment in aquifers of the Baton Rouge area, Louisiana: Louisiana Department of Conservation, Geological Survey, and Department of Public Works Water Resources Bulletin 13, 45 p.
Rosenshein, J. S., 1988, Hydrogeology of North America, region 18; Alluvial valleys, *in* Back, W., Rosenshein, J. S., and Seaber, P. R., eds., Hydrogeology: Boulder, Colorado, Geological Society of America, The Geology of North America, v. O-2, p. 165–176.
Sayre, A. N., and Bennett, R. P., 1942, Recharge, movement, and discharge in the Edwards Limestone reservoir, Texas: American Geophysical Union Transaction, pt. 1, p. 19–27.
Scott, T. M., 1989, The lithostratigraphy and hydrostratigraphy of the Floridan aquifer system in Florida, *in* Scott, T. M., Arthur, J., Ruport, F., Upchurch, S., and Randazzo, A., eds., The lithostratigraphy and hydrostratigraphy of the Floridan aquifer system in Florida; 28th International Geological Congress Guidebook T185, American Geophysical Union, p. 2–9.
Sharp, J. M., Jr., 1988, Alluvial aquifers along major rivers, *in* Back W., Rosenshein, J. S., and Seaber, P. R., eds., Hydrogeology: Boulder, Colorado, Geological Society of America, The Geology of North America, v. O-2, p. 273–282.
——, 1990, Stratigraphic, geomorphic, and structural controls of the Edwards aquifer, Texas, U.S.A., *in* Simpson, E. S., and Sharp, J. M., Jr., eds., Selected Papers on Hydrogeology: Heise, Hannover International Association of Hydrogeologists, v. 1, p. 67–82.
Sharp, J. M., Jr., and Clement, T. J., 1988, Hydrochemical facies as hydraulic boundaries in karstic aquifers; The Edwards aquifer, U.S.A., *in* Karst hydrogeology and karst environment protection, Proceedings of the 21st International Association of Hydrogeologists Congress: Guilin, Peoples Republic of China, v. 2, p. 841–845.
Sharp, J. M., Jr., and Germiat, S. J., 1990, Risk assessment and causes of subsidence along the Texas Gulf Coast, *in* Fairbridge, R. W., and Paepe, R., eds., Greenhouse effect, sea level, and drought: Dordrecht, Kluwer Academic Publishers (in press).
Sharp, J. M., Jr., and McBride, E. F., 1989, Sedimentary petrology; A guide to paleohydrogeologic analyses; Example of sandstones from the northwest Gulf of Mexico: Journal of Hydrology, v. 108, p. 367–386.
Sharp, J. M., Jr., and 12 others, 1988, Diagenetic processes in northwest Gulf of Mexico sediments, *in* Chilingarian, G. V., and Wolf, K. H., eds., Diagenesis II: Elsevier Science Publishers, p. 43–113.
Smith, G. E., Galloway, W. E., and Henry, C. D., 1982, Regional hydrodynamics and hydrochemistry of the uranium-bearing Oakville aquifer (Miocene) of south Texas: Texas Bureau of Economic Geology Report of Investigation 124, 31 p.
Stringfield, V. T., 1936, Water in the Florida Peninsula: U.S. Geological Survey Water-Supply Paper 773-C, p. 116–195.
Thayer, P. A., and Miller, J. A., 1984, Petrology of lower and middle Eocene carbonate rocks: Transactions of the Gulf Coast Association of Geological Societies, v. 34, p. 421–434.
Turcan, A. N., Jr., Wesselman, J. B., and Kilburn, C., 1966, Interstate correlation of aquifers, southwestern Louisiana and southeastern Texas: U.S. Geological Survey Professional Paper 550-D, p. D231–D236.
Wesselman, J. B., 1983, Structure, temperature, pressure, and salinity of Cenozoic aquifers of south Texas: U.S. Geological Survey Hydrological Investigations Atlas HA-654, 1 sheet.
Woodruff, C. M., Jr., and Abbott, P. L., 1979, Drainage-basin evolution and aquifer development in a karstic limestone terrain, south-central Texas, U.S.A.: Earth Surface Processes, v. 4, p. 319–334.

Manuscript Accepted by the Society May 7, 1990

ACKNOWLEDGMENTS

We thank Bill Back, Hayes Grubb, Tony Randazzo, and, of course, Amos Salvador for their reviews and encouragement. Acknowledgment is also made to the donors of the Petroleum Research Fund of the American Chemical Society for partial support of the background research. Manuscript preparation was funded by the Owens-Coates Fund of the Geology Foundation, the University of Texas at Austin. Rosemary Brant assisted with the editing; Jeff Horowitz and Karen Bergeron drafted the figures.