CHAPTER THREE: GEOLOGY OF THE NEW ORLEANS REGION

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3.1 General Overview of the Geology of New Orleans

3.1.1 Introduction

Hurricane Katrina brought devastation to New Orleans and the surrounding Gulf Coast Region during late August 2005. Although there was wind damage in New Orleans, most of the devastation was caused by flooding after the levee system adjacent to Lake Pontchartrain, Lake Borgne and Inner Harbor areas of the city systematically failed. The storm surge fed by winds from Hurricane Katrina moved into Lake Pontchartrain from the Gulf of Mexico through Lake Borgne, backing up water into the drainage and navigation canals serving New Orleans. The storm surge overwhelmed levees surrounding these engineered works, flooding approximately 80% of New Orleans.

Although some levees/levee walls were overtopped by the storm surge, the London Avenue and 17th Street drainage canal walls were not overtopped. They appear to have suffered foundation failures when water rose no higher than about 4 to 5 feet below the crest of the flood walls. This occurrence has led investigators to carefully investigate and characterize the foundation conditions beneath the levees that failed. A partnership between the U.S. Geological Survey's Mid-Continent Geologic Science Center and the University of Missouri – Rolla, both located in Rolla, MO, was established in the days immediately after the disaster to make a field reconnaissance to record perishable data. This engineering geology team was subsequently absorbed into the forensic investigation team from the University of California, Berkeley, funded by the National Science Foundation.

The team has taken multiple trips to the devastated areas. During these trips team members collected physical data on the levee failures, much of which was subsequently destroyed or covered by emergency repair operations on the levees. Our team also logged a series of subsurface exploratory borings to characterize the geological conditions present in and around the levee failure sites.

3.1.2 Evolution of the Mississippi Delta beneath New Orleans

The Mississippi River drains approximately 41% of the Continental United States, a land area of 1.2 million mi^2 (3.2 million km^2). The great majority of its bed load is deposited as subaerial sediment on a well developed flood plain upstream of Baton Rouge, as opposed to subaqueous deposits in the Gulf of Mexico. The Mississippi Delta has been lain down by an intricate system of distributary channels; that periodically overflow into shallow swamps and marshes lying between the channels (Figure 3.1, upper). The modern delta extends more or less from the present-day position of Baton Rouge (on the Mississippi River) and Krotz Springs (on the Atchafalaya River). The major depositional lobes are shown in Figure 3.1 (lower).

Between 12,000 and 6,000 years ago sea level rose dramatically as the climate changed and became warmer, entering the present interglacial period, which geologists term the Holocene Epoch (last 11,000 years). During this interim sea level rose approximately 350 feet, causing the Gulf of Mexico to retreat into southeastern Louisiana inundating vast tracts of coastline. By 7,000 years ago sea level had risen to within about 30 feet of its present level. By 6,000 years ago the Gulf had risen to within 10 to 15 feet of its present level.

The modern Mississippi Delta is a system of distributary channels that have deposited large quantities of sediment over the past 6,000 to 7,000 years (Figure 1 –upper). Six major depositional lobes, or coalescing zones of deposition, have been identified, as presented in Figure 3.1 (lower). In southeastern Louisiana deltaic sedimentation did not begin until just the last 5,000 years (Saucier, 1994). Four of these emanate from the modern Mississippi River and two from the Atchafalaya River, where the sediments reach their greatest thickness. The St. Bernard Delta extending beneath Lake Borgne, Chandeleur and Breton Sounds to the Chandeleur and Breton Shoals was likely deposited between 600 and 4,700 years ago. The 50+ miles of the modern Plaquemines-Balize Delta downstream of New Orleans has all been deposited in just the last 800 to 1,000 years (Darut et al. (2005).

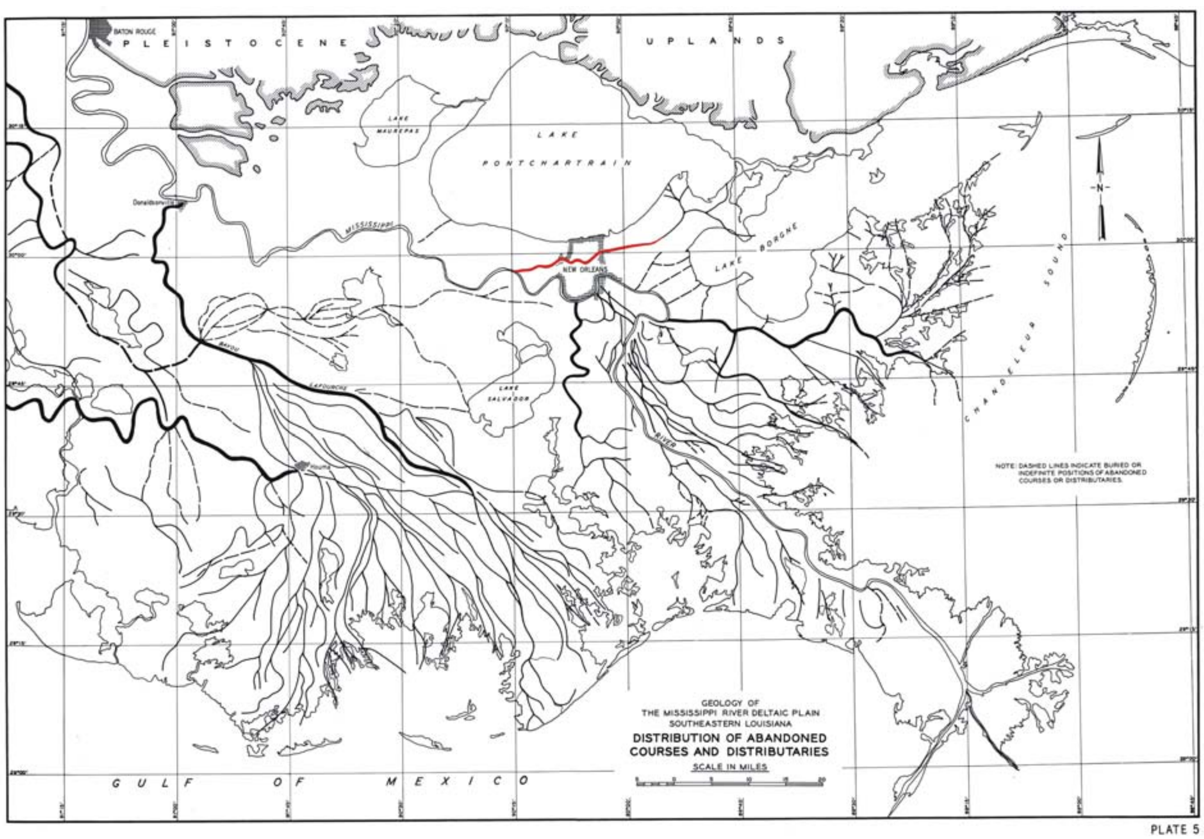

Figure 3.1 (upper): Areal distribution of abandoned channels and distributaries of the Mississippi River (from Kolb, 1958). The Metairie Ridge distributary channel (highlighted in red) lies between two different depositional provinces in the center of New Orleans (shown in Figure 3.6).

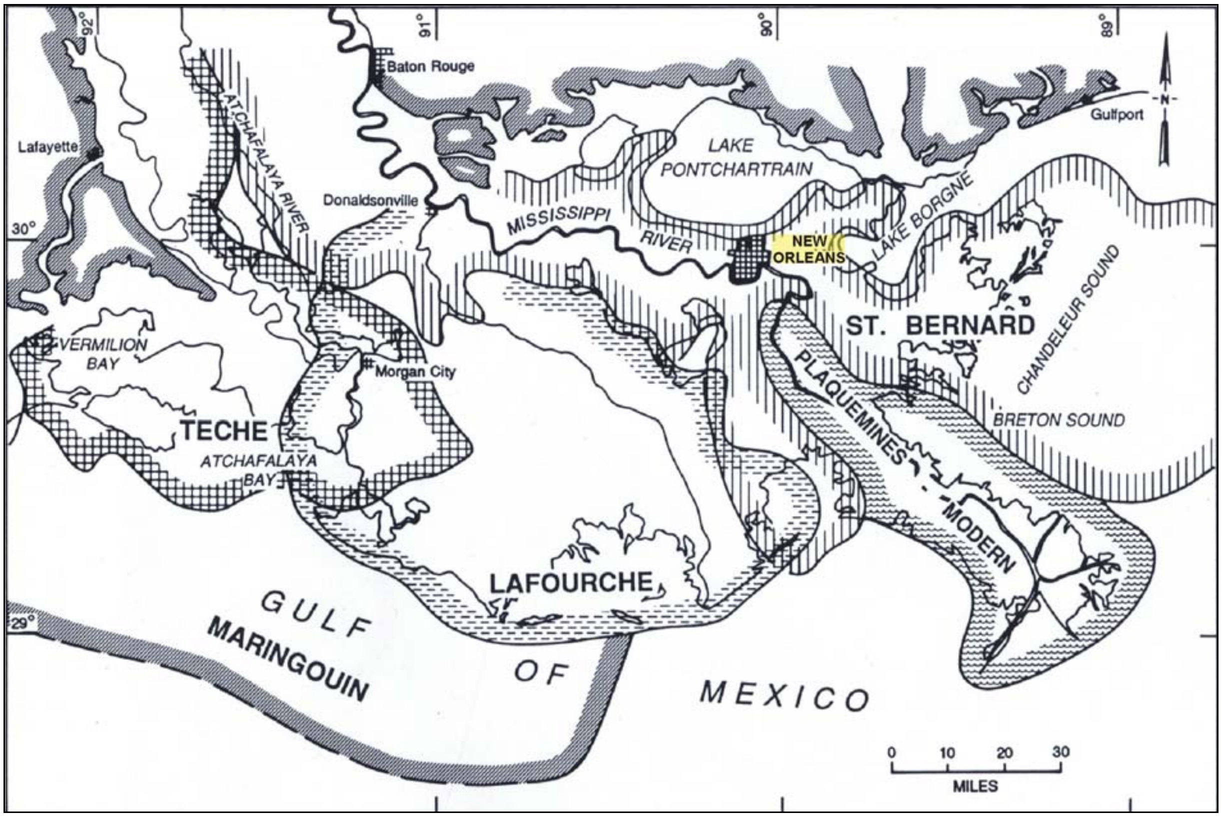

Figure 3.1 (lower): Major depositional lobes identified in lower Mississippi Delta around New Orleans, taken from Saucier (1994).

During this same period (last 7,000 years) the Mississippi River has advanced its mouth approximately 200 river miles into the Gulf of Mexico. The emplacement of jetties at the river's mouth in the late 1870's served to accelerate the seaward extension of the main distributary passes (utilized as shipping channels) to an average advance of about 70 meters per year, or about six times the historic rate (Coleman, 1988; Gould, 1970). The combination of channel extension and sea level rise has served to flatten the grade of the river and its adjoining flood plains, diminishing the mean grain size of the river's bed load, causing it to deposit increasing fine grained sediments. Channel sands are laterally restricted to the main stem channel of the Mississippi River, or major distributary channels, or "passes", like the Metairie-Gentilly Ridge. The vast majority of the coastal lowland is infilled with silt, clay, peat, and organic matter.

Geologic sections through the Mississippi Embayment show that an enormous thickness of sediment has been deposited in southern Louisiana (Figure 3.2). During the Quaternary Period, or Ice Ages, (11,000 to 1.6 million years ago) the proto Mississippi River conveyed a significantly greater volume of water on a much steeper hydraulic grade. This allowed large quantities of graveliferous deposits beneath what is now New Orleans, reaching thicknesses of up to 3600 feet (Figures 3.2 and 3.3). These stiff undifferentiated Pleistocene sands and gravels generally lie between 40 and 150 feet beneath New Orleans, and much shallower beneath Lake Pontchartrain and Lake Borgne (as one approaches the Pleistocene outcrop along the North Shore of Lake Pontchartrain).

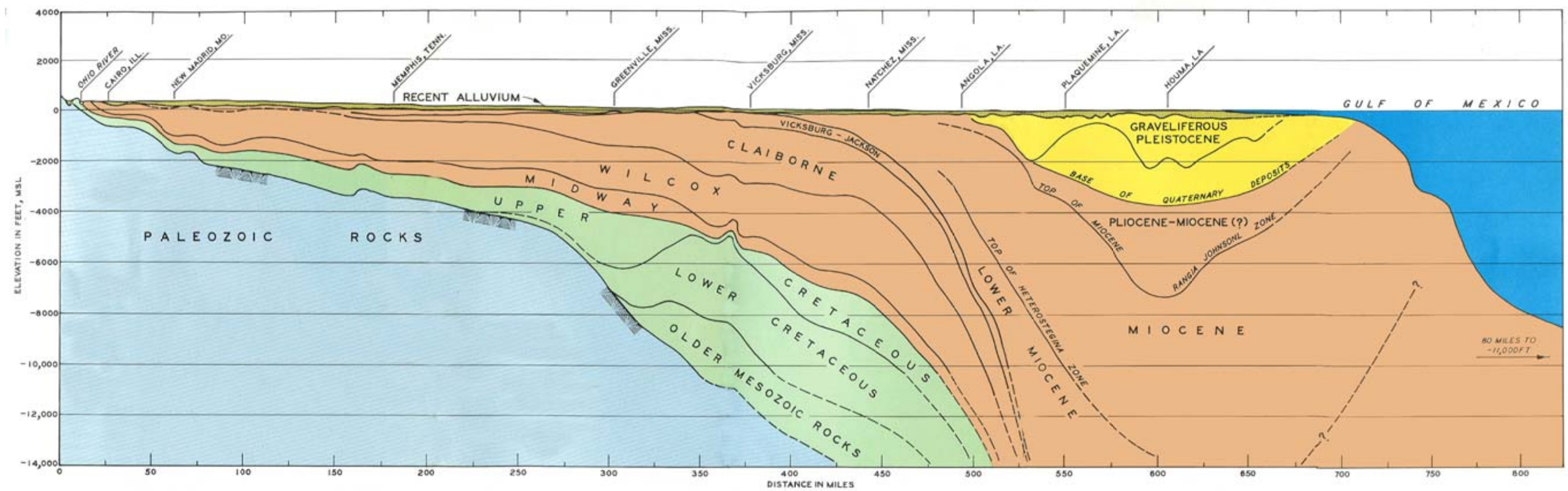

Figure 3.2: North-south geologic cross section through the central Gulf of Mexico Coastal Plain, along the Mississippi River Embayment (from Moore, 1972). Note the axis of the Gulf Coast Geosyncline beneath Houma, LA, southwest of New Orleans. In this area the Quaternary age deposits reach a thickness of 3600 ft.

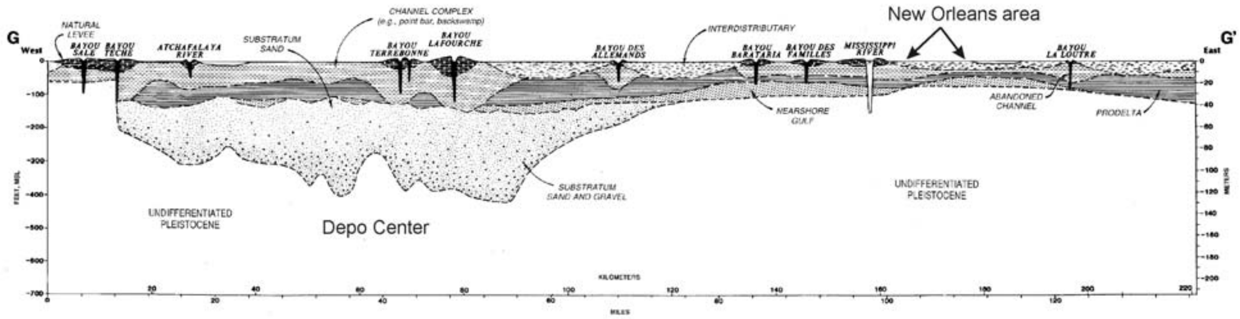

Figure 3.3: Transverse cross section in a west to east line, across the Mississippi River Delta a few miles south of New Orleans, cutting across the southern shore of Lake Borgne (modified from Saucier, 1994). New Orleans is located on a relatively thin deltaic plain towards the eastern side of the delta's depositional center, which underlies the Atchafalaya Basin, west of New Orleans.

Just south of the Louisiana coast, the Mississippi River sediments reach thicknesses of 30,000 feet or more. The enormous weight of this sediment mass has caused the earth's crust to sag in this area, resulting in a structure known as the Gulf Geosyncline (Figure 3.2). Flow of mantle material from below the Gulf Geosyncline is causing an uplift along about the latitude of Wiggins, MS. This is one cause of subsidence in South Louisiana (discussed in Section 3.7.2).

Figure 3.4 presents a generalized geologic map of the New Orleans area, highlighting the salient depositional features. Depth contours on the upper Pleistocene age (late Wisconsin glacial stage) horizons are shown in red. Sea level was about 100 feet lower than present about 9000 years ago, so the -100 ft contour represents the approximate shoreline of the Gulf at that time, just south of the current Mississippi River channel. Figure 3.5 presents a more detailed view of the dissected late Wisconsin stage erosional surface beneath New Orleans. This system emanates from the Lake Pontchartrain depression and reaches depths of 150 feet below sea level where it is truncated by the modern channel of the Mississippi River, which is not as deeply incised. A veneer of interdistributary deltaic deposits covers this older surface and is widely recognized for having spawned differential settlement of the cover materials where variations in thickness are severe, such as the Garden District.

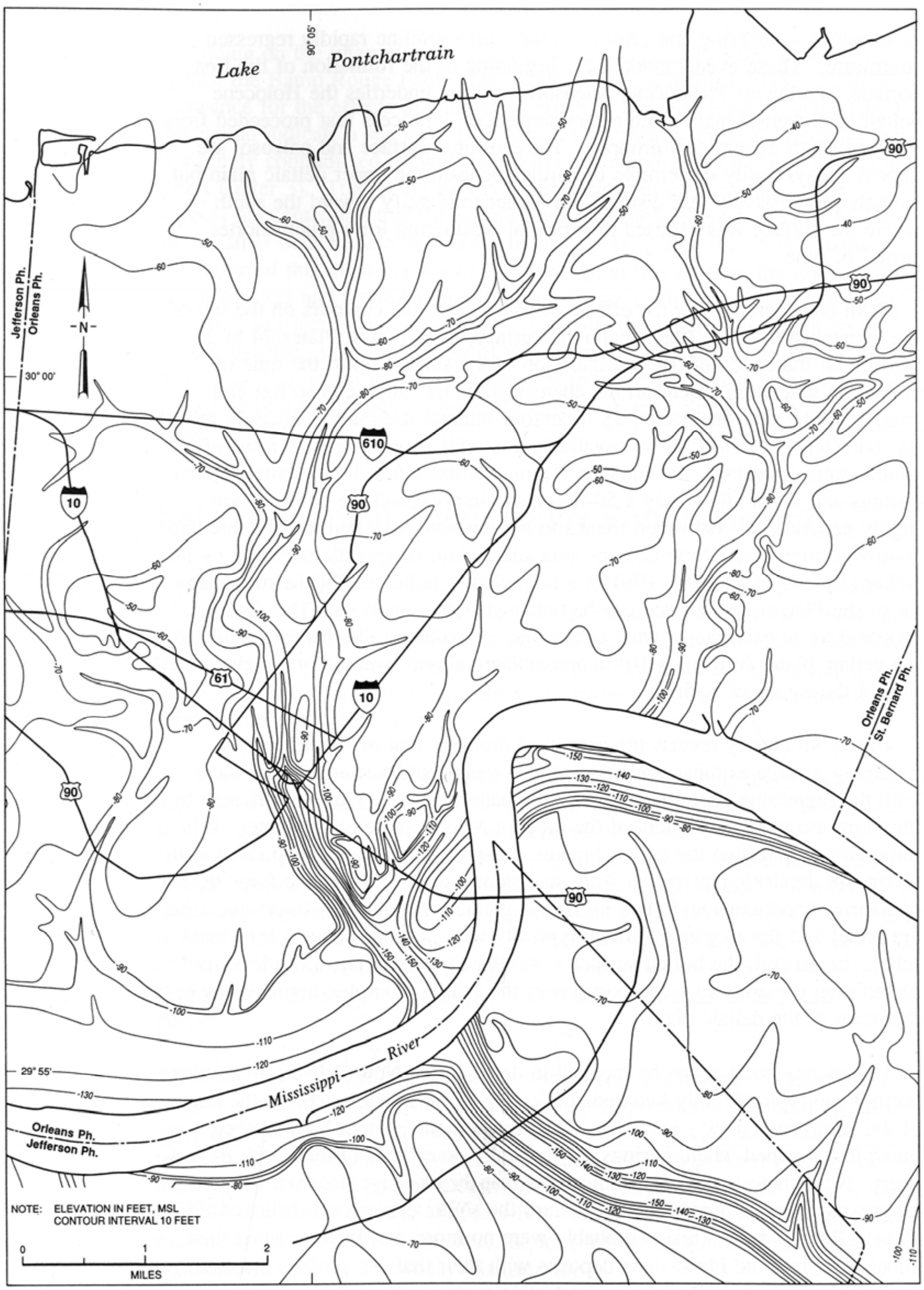

Figure 3.5: Contours of the entrenched surface of the Wisconsin glacial age deposits underlying New Orleans, taken from Saucier (1994). Note the well developed channel leading southward, towards what used to be the oceanic shoreline. This channel reaches a maximum depth of 150 feet below sea level.

3.1.3 Pine Island Beach Trend

Relict beach deposits emanating from the Pearl River are shown in stippled yellow on Figure 3.4. Saucier (1963) named these relict beaches the Pine Island and Miltons Island beach trends. These sands emanate from the Pearl River between Louisiana and Mississippi, to the northeast. The Miltons Island Beach Trend lies beneath the north shore of Lake Pontchartrain, while the Pine Island Beach Trend runs northeasterly, beneath the Lakeview and Gentilly neighborhoods of New Orleans up to the Rogolets. The Pine Island Beach Trend is believed to have been deposited when sea level had almost risen to its present level, about 4500 years ago. At that juncture, the rate of sea level rise began to slow and there was an unusually large amount of sand being deposited near the ancient shoreline by the Pearl River, which was spread westerly by longshore drift, in a long linear sand shoal, which soon emerged into a beach ridge along a northeast-southwest trend (Saucier, 1963). The subsequent development of accretion ridges indicate that shoreline retreat halted and the beach prograded southwestward, into what is now the Gentilly and Lakeview areas. By about 5,000 years ago, the beach has risen sufficiently to form a true barrier spit anchored to the mainland near the present Rigolets, with a large lagoon forming on its northern side (what is now Lake Pontchartrain, which occupies an area of 635 mi^2).

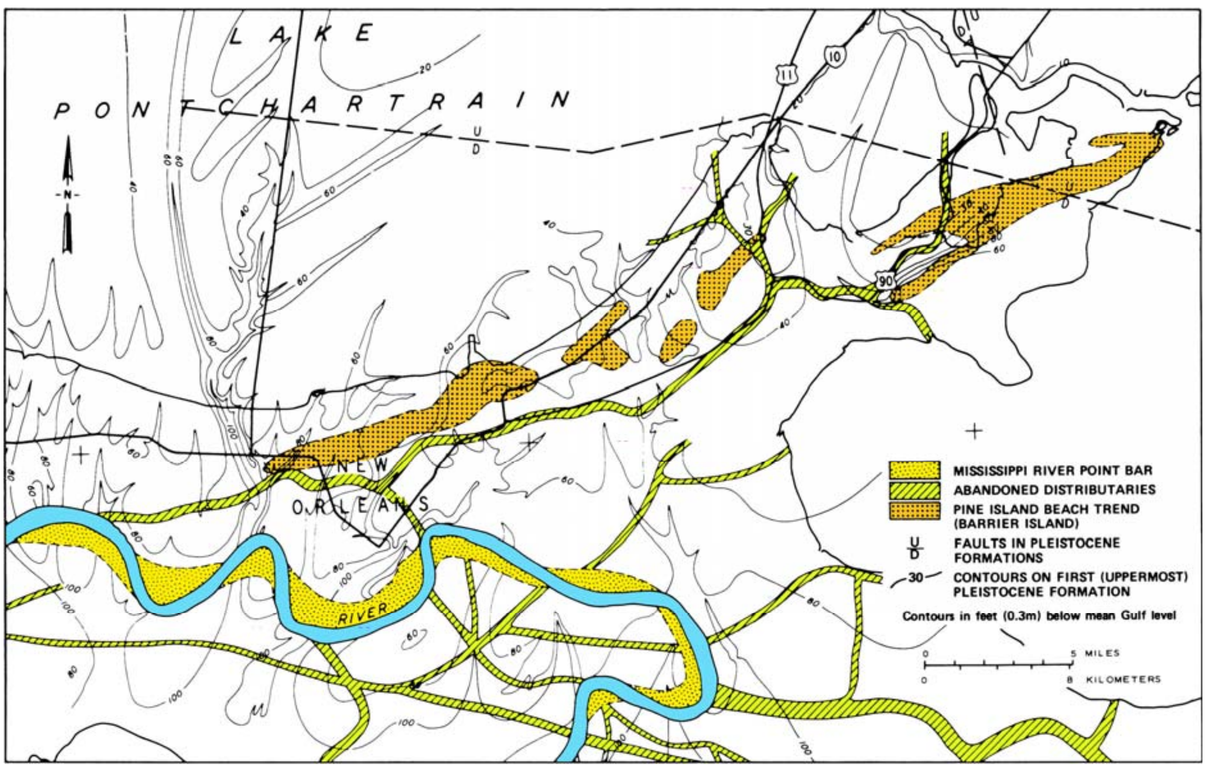

Figure 3.4: Pleistocene geologic map of the New Orleans area, taken from Kolb and Saucier (1982), modified from Kolb and Saucier (1982). The yellow stippled bands are the principal distributory channels of the lower Mississippi during the late Pleistocene, while the present channel is shown in light blue. The Pine Island Beach Trend is shown in the ochre dotted pattern. Depth contours on the upper Pleistocene age horizons are also shown.

Sometime after this spit formed, distributaries of the Mississippi River (shown as yellow bands on Figure 3.4) began depositing deltaic sediments seaward of the beach trend, isolating it from the Gulf of Mexico. The Pine Island Beach Trend was subsequently surrounded and buried by sediment and the Pine Island sands have subsided 25 to 45 feet over the past 5,000 years (assuming it once stood 5 to 10 feet above sea level). The distribution of the Pine Island Beach Trend across lower New Orleans is shown in Figure 3.6. The Pine Island sands reach thicknesses of more than 40 feet in the Gentilly area, but diminish towards the Lakeview area, pinching out near the New Orleans/Jefferson Parish boundary (close to the 17th Street Canal breach). The Pine Island beach sands created a natural border that helped form the southern shoreline of Lake Pontchartrain, along with deposition by the Mississippi River near its present course. Lake Pontchartrain was not sealed off entirely until about 3,000 years ago, by deposition in the St. Bernard's Deltaic lobe (Kolb, Smith, and Silva, 1975). The Pine Island Beach Trend peters out beneath Jefferson Parish, as shown in Figures 3.6 and 3.13.

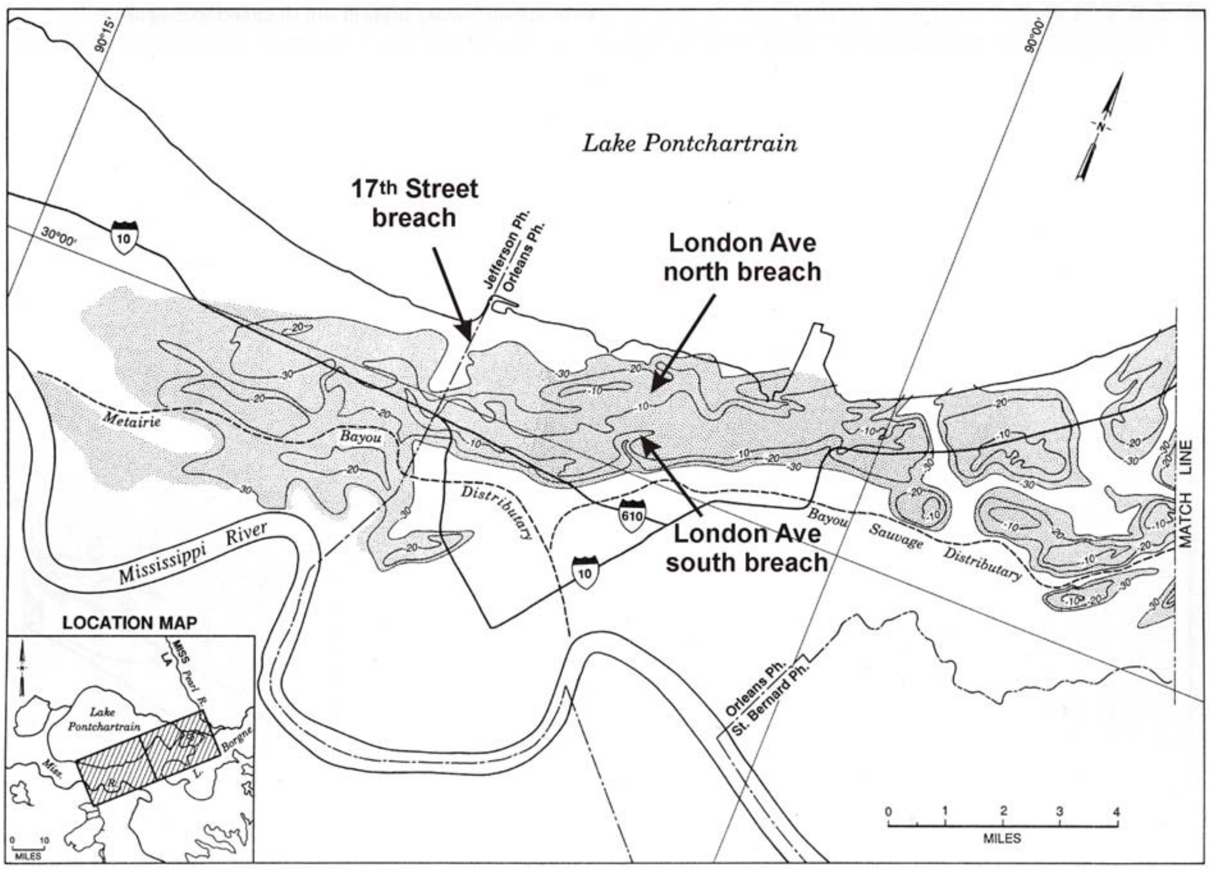

Figure 3.6 - Areal distribution and depth to top of formation isopleths for the Pine Island Beach Trend beneath lower New Orleans, modified from Saucier (1994).

3.1.4 Interdistributary Zones

Most of New Orleans' residential areas lie within what is called an interdistributary zone, underlain by lacustrine, swamp, and marsh deposits, shown schematically in Figure 3.7. This low lying area rests on a relatively thin deltaic plain, filled with marsh, swamp, and lacustrine sediments. The drainage canals were originally constructed between 1833-78 on interdistributary embayments, which are underlain by fat clays deposited in a quiet water, or paludal, environment (Kolb and Van Lopik, 1958).

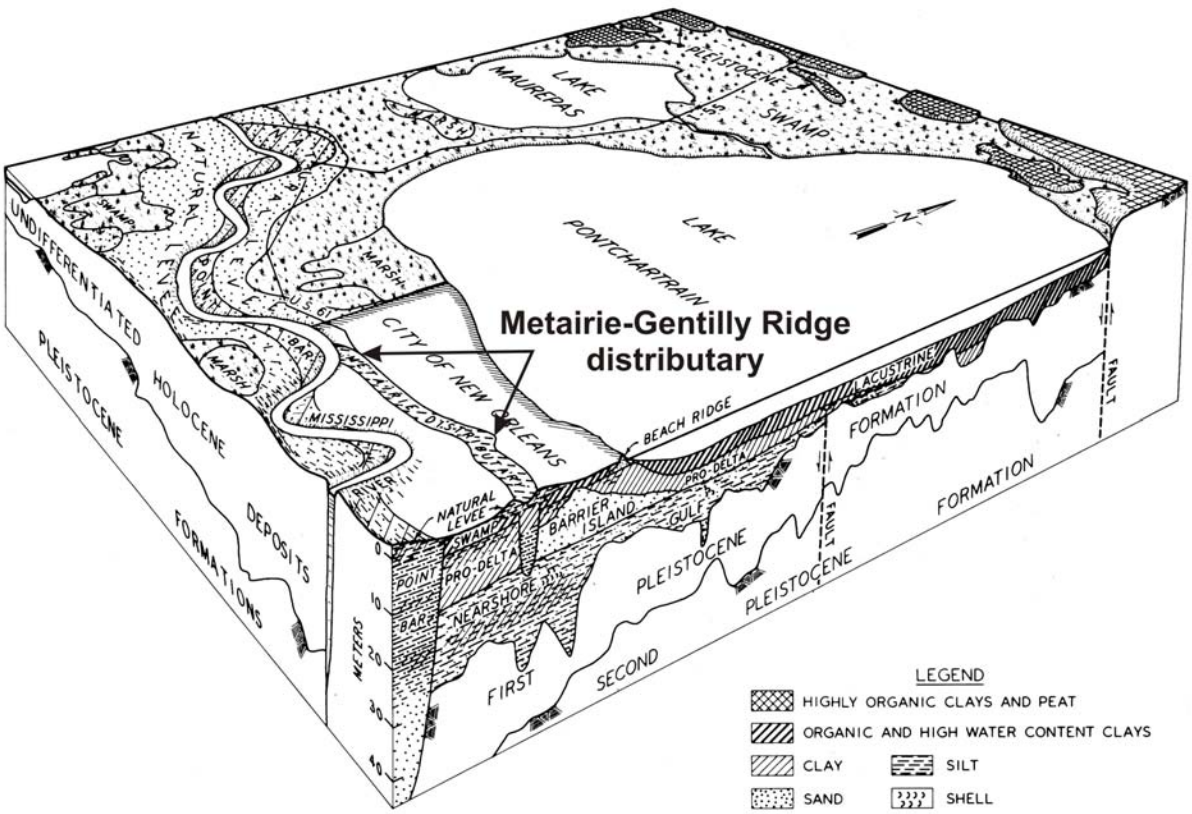

Figure 3.7: Block diagram of the geology underlying New Orleans (modified from Kolb and Saucier, 1982). The principal feature dividing New Orleans is the Metairie distributary channel, shown here, which extends to a depth of 50 feet below MGL and separates geologic regimes on either side. Note the underlying faults, especially that bounding the northern shore of Lake Pontchartrain.

Interdistributary sediments are deposited in low lying areas between modern distributory channels and old deltas of the Mississippi River, shown schematically in Figure 3.8. The low angle bifurcation of distributary streams promotes trough-like deposits that widen towards the gulfward. Sediment charged water spilling over natural channel levees tends to drop its coarse sediment closest to the channel (e.g. Metairie and Gentilly Ridges) while the finest sediment settles out in shallow basins between the distrubutaries. Fine-grained sediment can also be carried into the interdistributary basins through crevasse-splays well upstream, which find their way into low lying areas downstream. Storms can blow sediment-laden waters back upstream into basins, while hurricanes can dump sediment-laden waters onshore, though these may be deposited in a temporarily brackish environment.

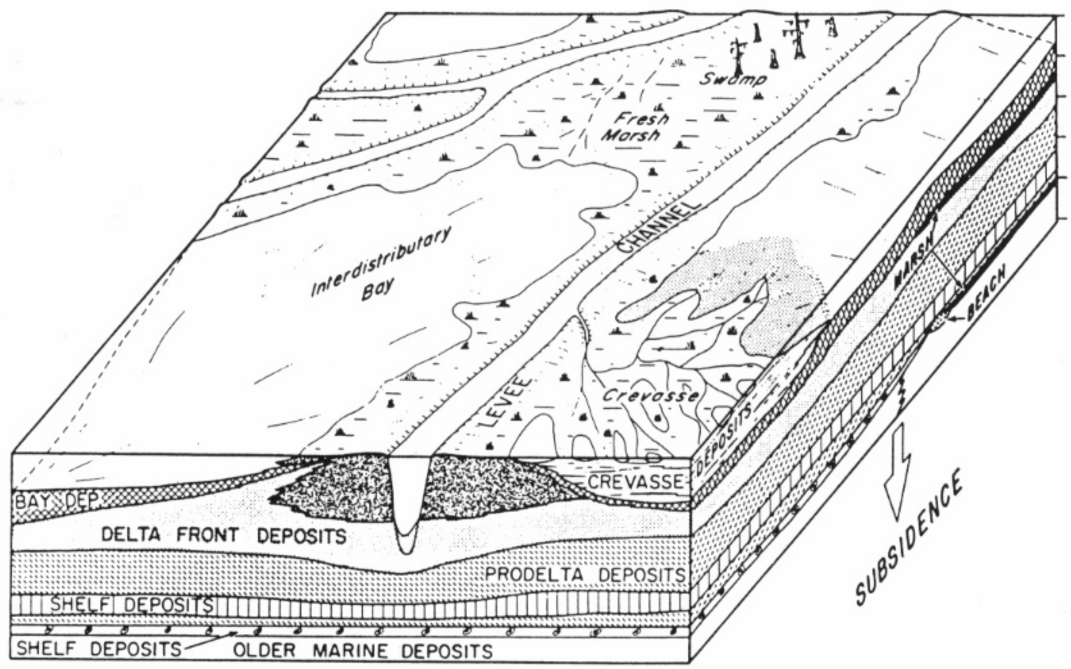

Figure 3.8: Block diagram illustrating relationships between subaerial and subaqueous deltaic environments in relation to a single distributary lobe (taken from Coleman and Roberts, 1991). The Lakeview and Gentilly neighborhoods of New Orleans are underlain by interdistributary sediments, overlain by peaty soils lain down by fresh marshes and cypress swamps.

Considerable thickness of interdistributary clays can be deposited as the delta builds seaward. Kolb and Van Lopik (1958) noted that interdistributary clays often grade downward into prodelta clays and upward into richly organic clays of swamp or marsh deposits. The demarcation between clays deposited in these respective environments is often indistinct. True swamp or marsh deposits only initiate when the water depth shallows sufficiently to support vegetation (e.g. cypress swamp or grassy marsh). The interdistributary zone is typified by organic clays, with about 60% by volume being inorganic fat clays, and 10% or less being silt (usually in thin, hardly discernable stringers). Kolb and Van Lopik (1958) reported cohesive strengths of interdistributary clays as ordinarily being something between 100 and 400 psf. These strengths, of course, depend also on the past effective overburden pressure.

Careful logging is required to identify the depositional boundary between interdistributary (marsh and swamp) and prodelta clays (Figure 3.9). The silt and fine sand fractions in interdistributary materials are usually paper-thin partings. Prodelta clays are typified by a massive, homogeneous appearance with no visible planes or partings. Geologically recent interdistributary clays, like those in lower New Orleans, also tend to exhibit underconsolidation, because they were deposited so recently. Interdistributary clays in vicinity of South Pass (45 miles downstream of New Orleans) exhibit little increase in strengths to depths of as much as 375 ft. This is because these materials were deposited rapidly, during the past 600 to 1,000 years, and insufficient time has passed to allow for normal consolidation, given the low drainage characteristics of the units. This phenomenon was noted and analyzed for offshore clays by Terzaghi (1956). The older prodelta clays underlying recent interdistributary clays tend to exhibit almost linear increase of density and strength with depth, because these materials were deposited very slowly. So, the environment of deposition greatly impacts soil strength.

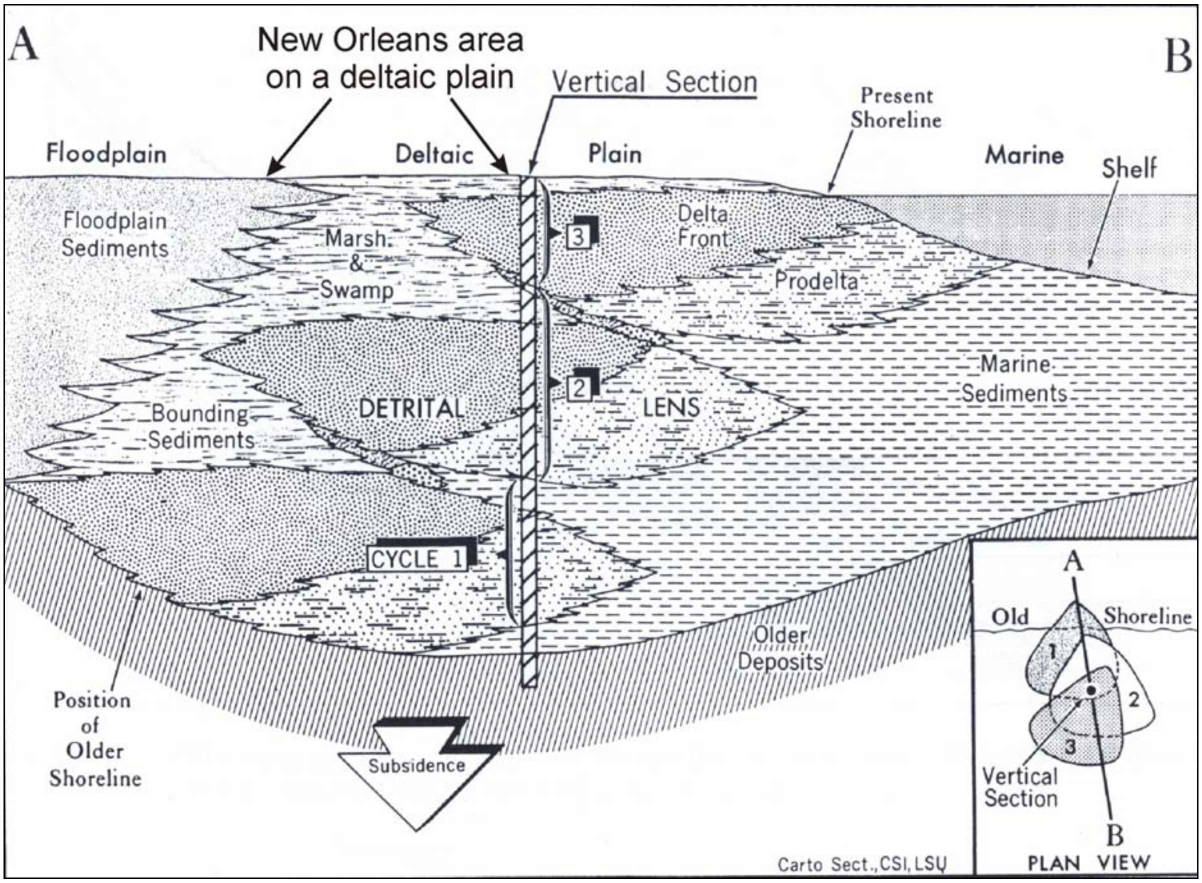

Figure 3.9: Sedimentary sequence caused by overlapping cycles of deltaic deposition, along a trend normal to that portrayed in the previous figure (modified from Coleman and Gagliano, 1964). As long as the distributary channel receives sediment the river mouth progrades seaward. Lower New Orleans lies on a deltaic plain with marsh and swamp deposits underlying the Lakeview and Gentilly neighborhoods and delta front deposits closer to Metairie-Gentilly Ridge, the nearest distributary channel.

3.1.5 Paludal environments

Paludal environments on the Mississippi River deltaic plain are characterized by organic to highly organic sediments deposited in swamps and marshes. Paludal environments are typified half-land and half-water, with water depths seldom exceeding two feet above mean gulf level. 90% of New Orleans is covered by swamp or marsh deposits (excluding filled areas). Lacustrine (lake) and tidal channel deposits can be complexly intermingled with swamp and marsh deposits.

3.1.5.1 Marshes

More than half of the New Orleans area was one covered by marshes, essentially flat areas where the only vegetation is grasses and sedges. Tufts of marsh grass often grow with mud or open water between them. When these expanses are dry, locals often refer to them as "prairies." As the marshes subside, grasses become increasingly sensitive to increasing salinity. As grasses requiring fresh water die out, these zones transition into a myriad of small lakes, eventually becoming connected to an intricate network of intertidal channels that rise and fall with diurnal tides. These are often noted on older maps as "brackish" or "sea marshes" to discern them from adjoining fresh water swamps and marshes (Figure 3.9).

Marsh deposits in New Orleans are typically comprised of organic materials in varying degrees of decomposition. These include peats, organic oozes, and humus formed as marsh plants die and are covered by water. Because the land is sinking, subaerial oxidation is limited, decay being largely fomented by anerobic bacteria. In stagnant water thick deposits consisting almost entirely of organic debris are commonplace. The low relative density of these materials and flooded nature provides insufficient effective stress to cause consolidation. As a consequence, the coastal marsh surface tends to "build down," as new vegetation springs up each year at a near-constant elevation, while the land continues to subside. In areas bereft of inorganic sediment, thick sequences of organic peat will accumulate, with low relative density. If the vegetation cannot keep pace with subsidence, marine waters will inundate the coastal marsh zone, as noted in the 1849 map in Figure 3.10.

Peats are the most common variety of marsh deposits in New Orleans. They usually consist of brown to black fibrous or felty masses of partially decomposed vegetative matter. Materials noted on many of the older boring logs as "muck" or "swamp muck" are usually detrital organic particles transported by marsh drainage or decomposed vegetative matter. These mucks are watery oozes that exhibit very low shear strength and cannot support any appreciable weight.

Inorganic sediments may also accumulate in marshes, depending on the nearness of a sediment source(s). Common examples are sediment-laden marine waters and muddy fluvatile waters. Brackish marsh deposits interfinger with fresh water deposits along the southern shore of Lake Pontchartrain, but dominate the shoreline around Lake Borgne. Floating marsh materials underlie much of the zone along old watercourses, like Bayou St. John and Bayou des Chapitoulas. Kolb and Van Lopik (1958) delineated four principal types of marsh deposits in New Orleans:

1. Fresh water marsh consists of a vegetative mat underlain by clays and organic clays. Fresh water marshes generally form as a band along the landward border of established marshes and in those areas repeatedly subjected to fresh water inundation. In most instances an upper mat of roots and plant parts at least 12 inches thick overlies fairly soft organic clays, which become firmer and less organic with depth. Peat layers are often discontinuous and their organic content is usually between 20 and 50%.

2. Floating marsh or flotant is a vegetative mat underlain by organic ooze. This is sometimes referred to as a "floating fresh marsh" or "floating three-cornered grass marsh." The vegetative mat is typically between 4 and 14 inches thick, floating on 3 to 15 ft of finely

divided muck or organic ooze, grading into clay with depth. The ooze often consolidates with depth and grades into a black organic clay or peat layer.

3. Brackish-fresh water marsh sequence consists of a vegetative mat underlain by peat. The upper mat of roots and recent marsh vegetation is typically 4 to 8 inches thick and underlain by 1 to 10 ft of coarse to medium textured fibrous peat. This layer is often underlain by a fairly firm, blue-grey clay and silty clay with thick lenses of dark grey clays and silty clays with high organic contents. The great majority of marsh deposits in New Orleans are of this type, with a very high peat and humus content, easily revealed by gravimetric water content and/or dry bulk density values.

4. Saline-brackish water marsh is identified by a vegetative mat underlain by clays. These are sometimes termed “drained salt marshes” on older maps. The typical sequence consists of a mat of roots, stems, and leaves from 2 to 8 inches thick, underlain by a fairly firm blue-grey clay containing roots and plant parts. Tiny organic flakes and particles are disseminated through the clay horizon. The clays tend to become less organic and firmer with depth. The saline to brackish water marsh occupies a belt ½ to 8 miles wide flanking the present day shoreline, along the coast.

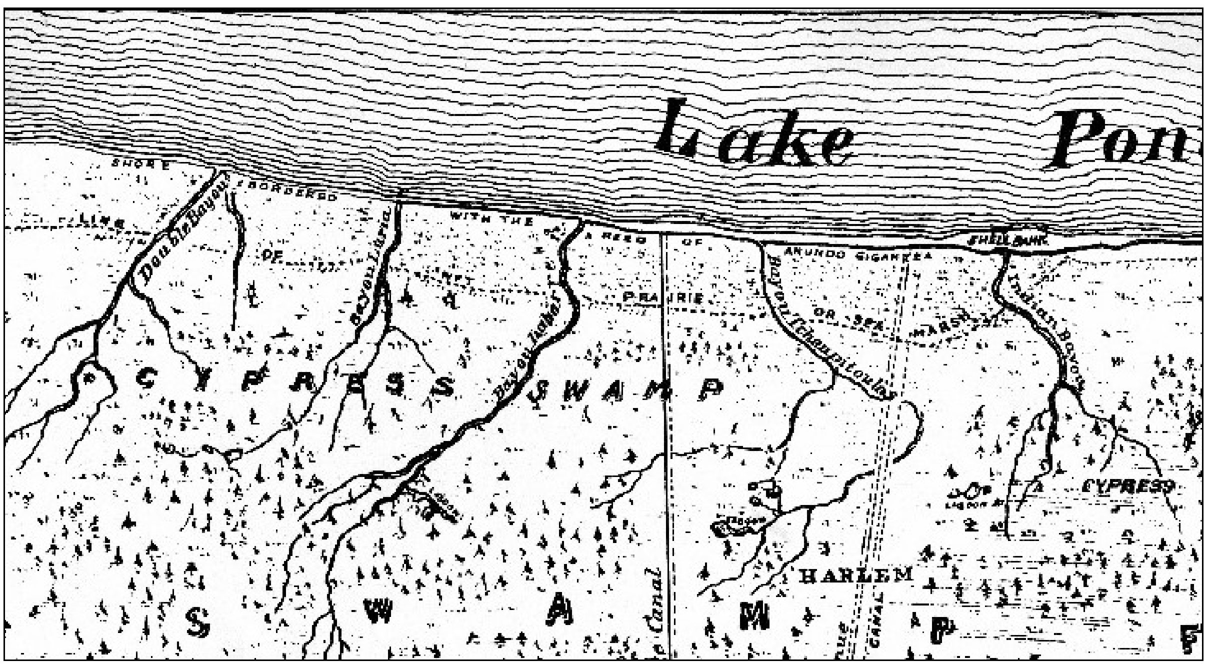

Figure 3.10: Portion of the 1849 flood map showing the mapped demarcation between brackish and fresh water marshes along Lake Pontchartrain (taken from WPA-LA, 1937). This delineation is shown on many of the historic maps, dating back to 1749.

The strengths of marsh deposits are generally quite low, depending on their water content. Embankments have been placed on vegetative mats underlain by ooze, supporting as much as 2 or 3 psi of loading, provided it is uniformly applied over reasonable distances, carefully (Kolb and Van Lopik, 1958). Field observations of sloped levees founded on such materials indicate failure at heights of around 6 feet, which exert pressures close to those cited above.

3.1.5.2 Swamps

Before development, swamps in the New Orleans were easily distinguishable from marshes because of the dense growth of cypress trees. All of the pre-1900 maps make reference to extensive cypress marshes in lower New Orleans, between the French Quarter and Lake Pontchartrain (Figure 3.11). Encountering cypress wood in boreholes or excavations is generally indicative of a swamp environment. These cypress swamps thrived in 2 to 6 feet of water, but cannot regenerate unless new influx of sediment is deposited in the swamp, reducing the water depth. Brackish water intrusion can also cause flocculation of clay and premature die out of the cypress trees.

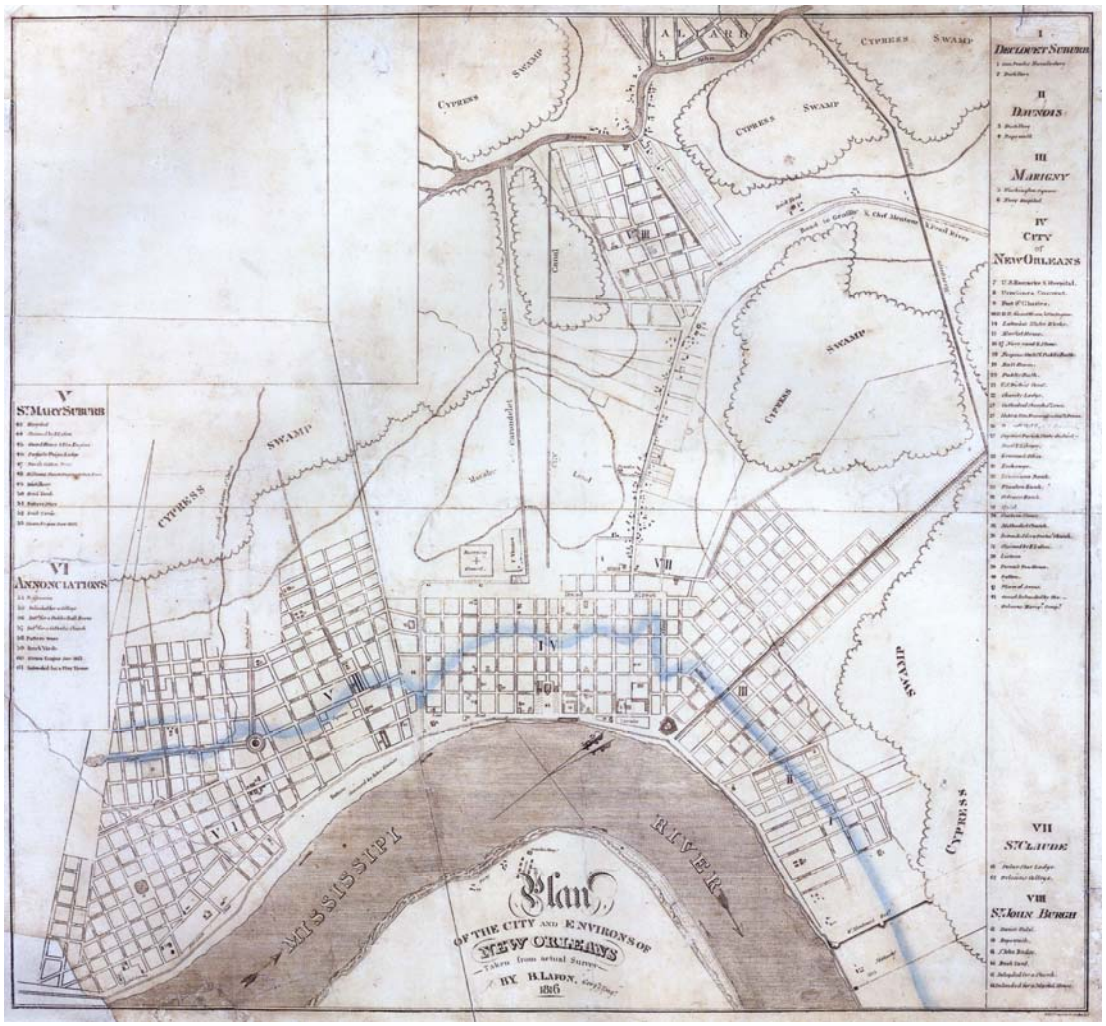

Figure 3.11: 1816 flood map of New Orleans showing areal distribution of cypress swamps north of the old French Quarter (from the Historic New Orleans Collection). These extended most of the distance to the Lake Pontchartrain shore.

Two layers of cypress swamp deposits are recognized to extend over large tracts of New Orleans (WPA-LA, 1937). The upper layer is the historic swamp occupying the original ground surface where infilling has occurred since the founding of the city in 1718; and the second; is a pervasive layer of cypress tree stumps that lies 20 to 30 feet below the ground surface, around -25 ft MGL (Mean Gulf Level) [Convert to NAVD88-2004.65 for consistency]. This older cypress forest was undoubtedly killed off and buried in a significant pre-historic flood event, fomented by considerable deposition of inorganic sediment. This sudden influx of sediment may have come from a crevasse-splay along the Mississippi River upstream of New Orleans, as in most of the damaging floods that befell the city prior to 1849.

There are two principal types of swamps in the New Orleans area, inland swamps and mangrove swamps. Inland swamps typically occupy poorly drained areas enclosed by higher ground; either natural levee ridges (like Metairie Ridge) or, much older (Pleistocene age) Prairie Terraces. These basins receive fresh water from overflow of adjacent channels during late spring and early summer runoff. The trees growing in inland swamps are very sensitive to increases in salinity, even for short-lived periods. Continued subsidence allows eventual encroachment of saline water, gradually transforming the swamp to a grassy marsh. The relative age of the tree die-off is readily seen in the form of countless dead tree trunks, followed by stumps, which become buried in the marsh that supersedes the swamp. As a consequence, a thin veneer of marsh deposits often overlies extensive sequences of woody swamp deposits. The converse is true in areas experiencing high levels of sedimentation, such as those along the historic Mississippi and Atchafalaya River channels, where old brackish water marshes are buried by more recent fresh water swamp deposits. Swamp deposits typically contain logs, stumps, and arboreal root systems, which are highly permeable and conductive to seepage.

Mangrove swamps are the variety that thrives in salt water, with the two principal varieties being black and honey mangrove. Mangrove swamps are found along the distal islands of the Mississippi Delta, such as Timbalier, Freemason North, and the Chandeleur Islands, well offshore. Mangrove swamps also fringe the St. Bernard Marsh, Breton and Chandeleur Sounds, often rooting themselves on submerged natural levees. Mangrove swamps can reach heights of 20 to 25 feet in Plaquemines Parish. A typical soil column in a mangrove swamp consists of a thin layer of soft black organic silty clay with interlocking root zone that averages 5 to 12 inches thick. Tube-like roots usually extend a few inches above the ground surface. Thicknesses of five feet or more are common. Where they grow on sandy barrier beaches, the mangrove swamps thrive on the leeward side, where silts and clays intermingle with wash-over sands off the windward side, usually mixed with shells.

Surficial swamp deposits provide the least favorable foundations for structures and man-made improvements, like streets and buried utilities. Kolb and Saucier (1982) noted that the amount of structural damage in New Orleans was almost directly proportional to the thickness of surficial organic deposits (swamps and marshes). This peaty surface layer reaches thicknesses of up to 16 ft, as shown in Figure 3.12. Most of this foundation distress is attributable to differential settlement engendered by recent de-watering (discussed in Section 3.7.4).

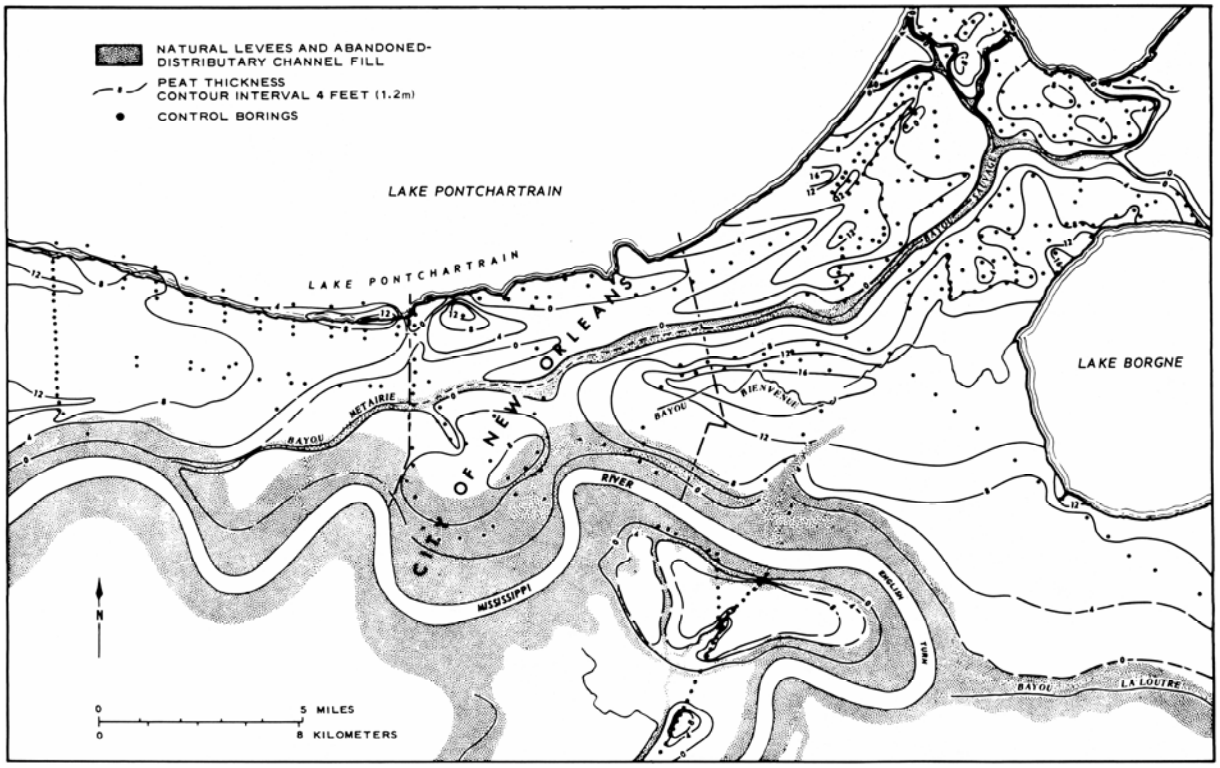

Figure 3.12: Distribution and apparent thickness of surficial peat deposits in vicinity of New Orleans, taken from Kolb and Saucier (1982) and Gould and Morgan (1962).

3.1.5.3 Lacustrine deposits

Lacustrine deposits are also deposited in a paludal environment of deltaic plains. This sequence most often occurs as marshes deteriorate (from lack of sediment) or subside (or both). These lakes vary in size, from a few feet in diameter to the largest, Lake Salvador (a few miles southwest of New Orleans), which measures 6 by 13 miles. Lake Pontchartrain (25 x 40 miles) is much larger, but is not a true marshland lake. The depth of these lakes varies from as little as 1.5 feet to about 8 feet (Lake Pontchartrain and Lake Borgne average 15 and 10 feet deep, respectively).

Small inland lakes within the marsh environment usually evolve from subsidence and erosion from wind shear and hurricane tides. Waves set up a winnowing action which concentrates the coarser material into the deepest portion of the lake. These lakes are generally quite shallow, often only a foot or two deep, even though up to a mile long. They are simply water-filled depressions on the underlying marsh, often identified in sampling by fine grained oozes overlying peats and organic clays of the marsh that preceded the transition to lake. The ooze become increasingly cohesive with age and depth, but is generally restricted to only 1 to 3 feet in thickness in small inland lakes.

Transitional lakes are those that become larger and more numerous closer to the actively retreating shoreline of the delta. These lake waters are free to move with the tides and currents affecting the open water of adjacent bays and sounds. Fines are often winnowed from the beds of these lakes and moved seaward, leaving behind silts and fine sands.

Sediments in these lakes are transitional between inland lakes and the largely inorganic silty and sandy materials flooring bays and sounds.

Large inland lakes are the only lacustrine bodies where significant volumes of sediment are deposited. Principal examples would be the western side of Lake Borgne, Lake Pontchartrain, and Lake Maurepas, among others. Lacustrine clays form a significant portion of the upper 20 to 30 feet of the deltaic plain surrounding New Orleans. Lake Pontchartrain appears to have been a marine water body prior to the deposition of the Metairie Ridge distributary channel, which formed its southern shoreline, sealing it off from the Gulf. The central and western floor of Lake Pontchartrain is covered by clays, but the northern, eastern and southern shores are covered by silts and sands, likely due to the choppy wave-agitated floor of the shallow lake. Deeper in the sediment sequence oyster shells are encountered, testifying that saline conditions once existed when the lake was open to the ocean. The dominant type of mollusk within Lake Pontchartrain today is the clam Rangia cuneata, which favors brackish water. Dredging for shells was common in Lake Pontchartrain until the late 1970's.

During Hurricanes Katrina and Rita in 2005, wind shear removed extensive tracts of marsh cover, creating 118 square miles of new water surface in the delta. Forty-one square miles of shear-expanded pools were added to the Breton Sound Basin within Plaquemines Parish. This was more erosion and land loss than had occurred during the previous 50 years combined (Map USGS-NWRC 2006-11-0049).

3.1.6 Recognition keys for depositional environments

Marsh deposits are typified by fibrous peats; from three principal environments: Fresh water marshes; 2) floating marsh – roots and grass sitting on an ooze of fresh water; and 3) saltwater marshes along the coast. The New Orleans marsh tends to be grassy marsh on a flat area that is "building down," underlain by soft organic clays. Low strength smectite clays tend to flocculate during brackish water intrusions, most commonly triggered by hurricanes making landfall in the proximate area.

Typical recognition keys for depositional environments have been summarized as follows.

- Cypress wood = fresh water swamp
- Fibrous peaty materials = marshes
- Fat Clays with organics; usually lacustrine. A pure fat clay has high water content (w/c) and consistency of peanut butter
- Interdistributary clays; paludual environments; lakes - Silt lenses when water is shallow and influenced by wind swept waves
- Lean clays CL Liquid Limit (LL) <50, silty and w/c <60%
- Fat clays CH Liquid Limit (LL) >50 no silt and w/c >70%

Abandoned meanders result in complex mixtures of channel sands, fat clay, lean clay, fibrous peat, and cypress swamp materials, which can be nearly impossible to correlate linearly between boreholes. The New Orleans District of the Corps of Engineers has historically employed 3-inch diameter Steel Shelby tubes and 5-inch diameter piston sampler, referring to samples recovered from the 5-inch sampler as their "undisturbed samples." These are useful for characterizing the depositional environment of the soils. The larger diameter "undisturbed" samples are usually identified on boring logs and cross sections in the New Orleans District Design Memoranda by the modifier "U" for "undisturbed" samples (e.g. Boring prefixes X-U, UMP-X, MUE-X, MUG-X, and MUW-X).

3.1.6 Holocene Geology of New Orleans

The surficial geology of the New Orleans area is shown in Figure 3.13. The Mississippi River levees form the high ground, underlain by sands (shown as bright yellow in Figure 3.13). The old cypress swamps (shown in green) and grassy marshlands (shown in brown) occupied the low lying areas. The Mid-town area between the Mississippi and Metairie Ridge was an enclosed depression (shown in green) known as a "levee flank depression" (Russell, 1967). The much older Pleistocene age Prairie formation (shown in ochre) lies north of Lake Pontchartrain. This unit dips down beneath the city and is generally encountered at depths greater than 40 feet between the city (described previously).

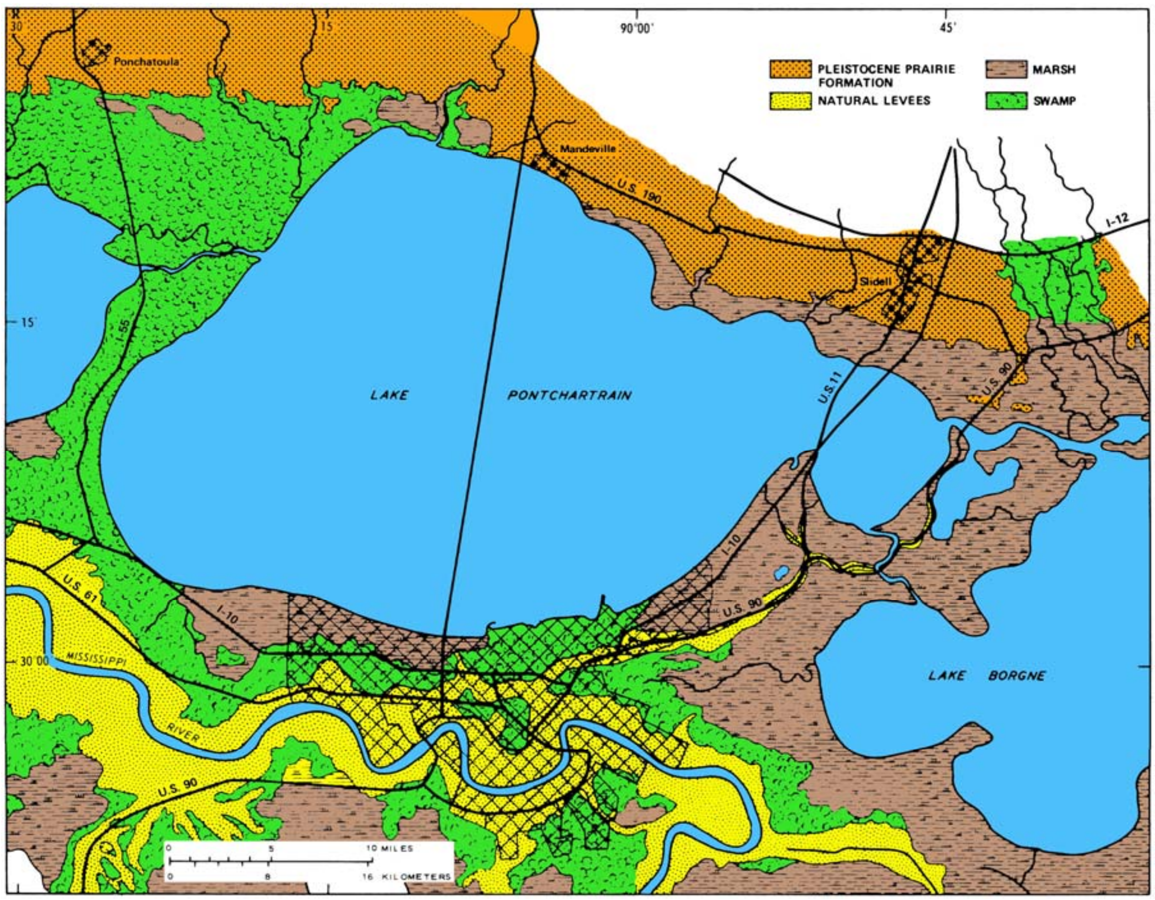

Figure 3.13: Geologic map of the greater New Orleans area, modified from Kolb and Saucier (1982). The sandy materials shown in yellow are natural levees, green areas denote old cypress swamps and brown areas are historic marshlands. The stippled zone indicates the urbanized portions of New Orleans.

The levee backslope and former swamplands north of Metairie Ridge are underlain by four principal stratigraphic units, shown in Figure 3.14. The surface is covered by a thin veneer of recent fill, generally a few inches to several few feet thick, depending on location. This is underlain by peaty swamp and marsh deposits, which are highly organic and susceptible to consolidation. Entire cypress trunks are commonly encountered in exploratory borings, as shown in Figure 3.15. This unit contains two levels of old cypress swamps, discussed previously, and varies between 10 and 40 feet thick, depending on location. The clayey material beneath this is comprised of interdistributary materials deposited in a paludal (quiet water) environment, dominated by clay, but with frequent clay stringers. This unit pinches out in vicinity of the London Avenue Canal and increases in thickness to about 15 feet beneath the 17th Street Canal, three miles west. Occasional discontinuous lenses of pure clay are often encountered which formed through flocculation of the clay platelets when the swamp was inundated by salt water during severe hurricanes.

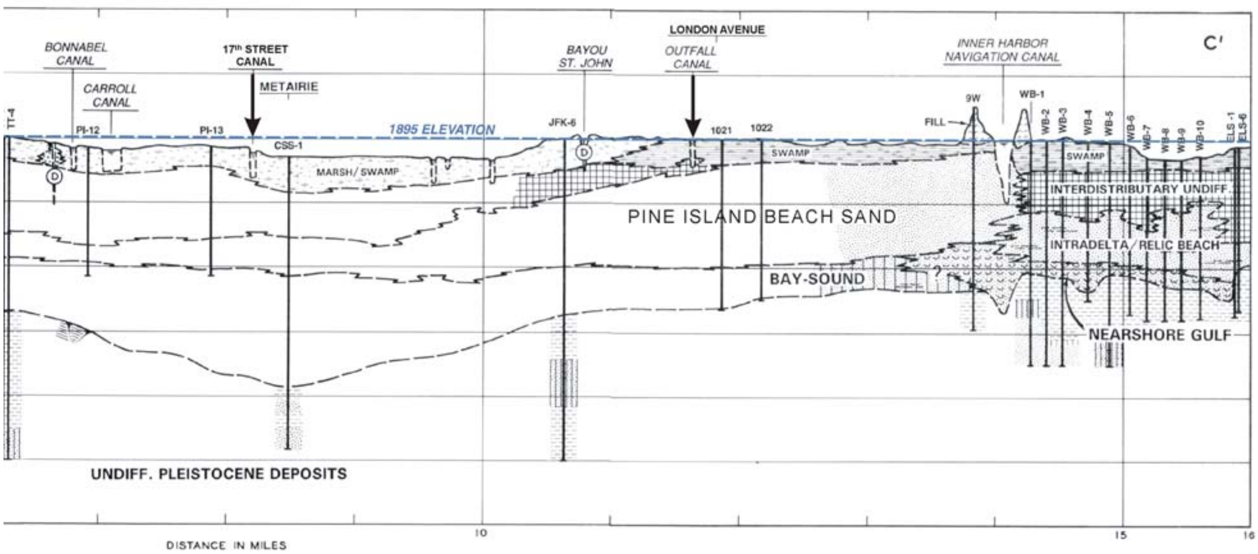

Figure 3.14: Geologic cross section along south shore of Lake Pontchartrain in the Lakeside, Gentilly, and Ninth Ward neighborhoods, where the 17th Street, London Avenue, and IHNC levees failed during Hurricane Katrina on Aug 29, 2005. Notice the apparent settlement that has occurred since the city survey of 1895 (blue line), and the correlation between settlement and non-beach sediment thickness. This east-west section was taken from Dunbar et al. (1994).

The area east of the Inner Harbor Navigation Canal (IHNC) is quite different (Figure 3.14), in that these deposits are dominated fine-grained lacustrine deposits deposited in proto Lake Pontchartrain, and the Pine Island Sands are missing. These lacustrine materials extend eastward and are characterized by clays and silty clays with intermittent silt lenses and organics.

Figure 3.15: Wood and other organic debris was commonly sampled in exploratory borings carried out after Hurricane Katrina throughout the city. This core contains wood from the old cypress marsh that was recovered near the 17th Street (Metairie Relief) Canal breach. Organic materials are decaying throughout the city wherever the water table has been lowered, causing the land surface to subside (photo by C. M. Watkins).

The lacustrine facies is underlain by the distinctive Pine Island Beach Sand, described previously. These relict beach sands thicken towards the east, closer to its depositional source. They reach a maximum thickness of about 30 ft. It thins westward towards Jefferson Parish, where it is only about 10 feet thick beneath the 17th Street Canal, as shown in Figure 3.14. The Pine Island sands are easily identified by the presence of mica in the quartz sand, and were likely transported from the mouth of the Pearl River by longshore drift (Saucier, 1963). Broken shells are common throughout the entire layer.

A bay sound deposit consisting of fine lacustrine clays begins just east of the Inner Harbor Navigation Canal; it begins near the 40 foot depth, has about a 10 foot thickness and continues to the west across the city, thickening along the way (Figure 3.14). It reaches its greatest thickness of about 35 feet just east of the 17th Street Canal. It is interesting to note that this area has experienced the greatest recorded settlement in the city, which may be attributable to dewatering of the units above this compressible lacustrine clay, increasing the effective stress acting on these materials (areas to the east are underlain by much more sand, which is less compressible).

The Holocene age deposits reach their greatest thickness just east of the 17th Street Drainage Canal where they are 80 feet thick (Figure 3.5). Undifferentiated Pleistocene deposits lie below these younger deposits.

For the most part, this area sits below sea level with the exception of the areas along old channels and natural levees. The Metairie-Gentilly Ridge lies above the adjacent portions of the city because it was an old distributary channel of the Mississippi River (Figure 1-

upper). The same is true for the French Quarter and Downtown New Orleans which are built on the natural sand levee of the Mississippi River.

Geology from the Inner Harbor Navigation Canal to the east becomes exceedingly complex. Although the surficial 10 feet consist of materials from an old cypress swamp, this is an area dominated by the Mississippi River and its distributaries, especially the old St. Bernard delta (See Figure 3.1-lower). Distributaries are common throughout the area and consist of sandy channels flanked by natural levees. 10-15 feet of interdistributary materials, mainly fine organic materials, are present between distributaries. Relic beaches varying in thickness from 10 to 15 feet are present below the interdistributary deposits. These beaches rest atop a 5-10 foot thick layer of nearshore deposits which are then followed by a thick sequence of prodelta clays leading out into the Gulf of Mexico.

3.1.7 Faulting and Seismic Conditions

Subsidence of the Gulf Geosyncline has led to numerous "growth" faults in South Louisiana. One group, the Baton Rouge Fault Zone (shown in Figure 3.7), is currently active and passes in an east-west direction along the north shore of Lake Pontchartrain. Localized faulting is also common near salt domes. There has been no known faulting in the New Orleans area which has been active in Holocene times. The area is seismically quiescent. The earthquake acceleration with a 10% chance of being exceeded once in 250 years is about 0.04g.

3.2 Geologic Conditions at 17th Street Canal Breach

3.2.1 Introduction

The 17th St. Canal levee (floodwall) breach is one of New Orleans' more interesting levee failures. It is one of several levees that did not experience overtopping. Instead, it translated laterally approximately 50 feet atop weak foundation materials consisting of organic-rich marsh and swamp deposits. Trees, fences, and other features on or near the levee moved horizontally but experienced very little rotation, indicating the failure was almost purely translational in nature.

3.2.2 Interpretation of Geology from Auger Borings

A series of continuously sampled borings was conducted and logged using 3-inch Shelby tubes in the vicinity of the 17th St. Outlet Canal levee failure on 2-1-2006 (east side) and 2-7-2006 (west side) to characterize the geology of the materials serving as a foundation for the levee embankments and floodwalls. Drilling on the east bank took place just behind (east) of an intact portion of the levee embankment that had translated nearly 50 feet while drilling on the west side took place directly across the canal from the middle of the eastern breach. This drilling uncovered a wide range of materials below the embankments and provided insights into the failure.

Drilling on the east side of the levee was started at approximately 2-3 feet above sea level. A thin layer of crushed rock fill placed by contractors working for the U.S. Army Corps of Engineers to provide a working surface at the break site was augered through before reaching the native materials. Upon drilling at the east side of the levee, organic matter was encountered almost immediately and a fetid swamp gas odor was noted. This organic matter consisted of low-density peat, humus, and wood fragments intermixed with fine sand, silt, and clay, possibly due to wind shear and wave action from prehistoric hurricanes. This area appears to have been near the distal margins of a historic slough, as shown in Figure 3.16. At 4-6 feet, highly permeable marsh deposits were encountered and drilling fluid began flowing from a CPT hole several feet away, indicative of almost instantaneous conductivity at this depth. The CPT was sealed with bentonite before proceeding to prevent further fluid loss. The bottom of this sample was recovered as a solid 3-inch core of orange-red cypress wood indicating that this boring had passed through a trunk of stump of a former, but geologically young, tree.

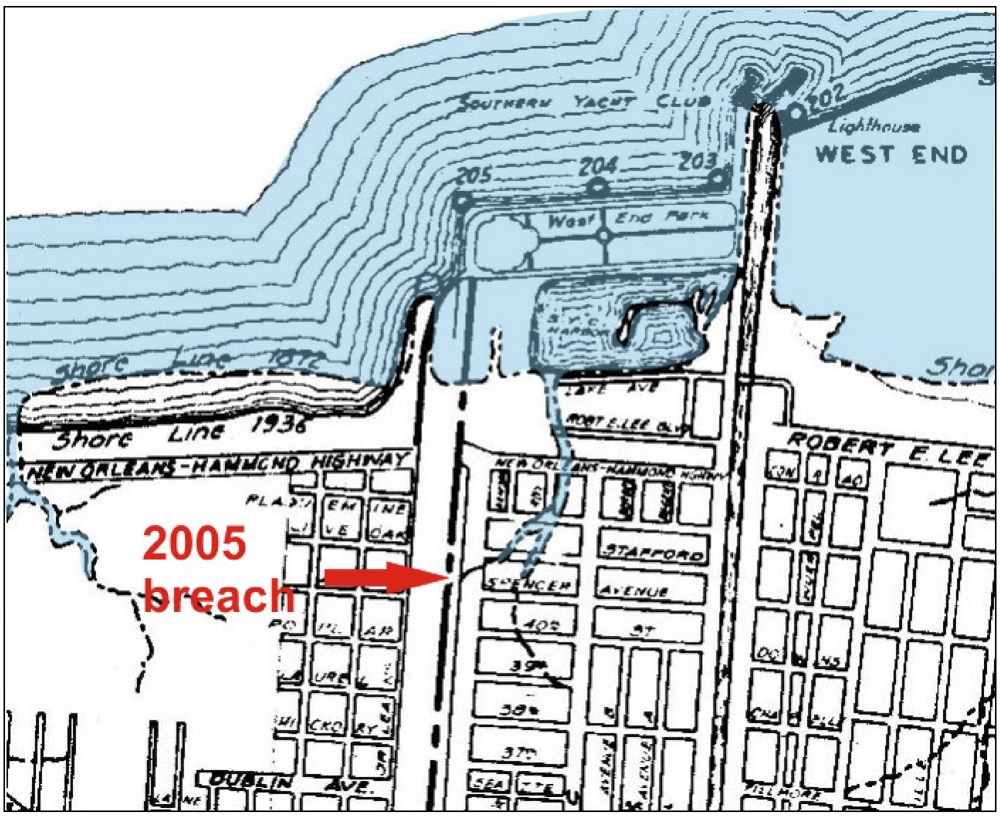

Figure 3.16: Overlay of 1872 map by Valery Sulakowski on the WPA-LA (1937) map, showing the 1872 shoreline and sloughs (in blue) along Lake Pontchartrain. Although subdivided, only a limited number of structures had been built in this area prior to 1946. The position of the 2005 breach along the east side of the 17th Street Canal is indicated by the red arrow.

A suspected slide plane was discovered at a depth between 8.3 and 11 feet below the ground surface depending on the location of the borings, indicative of an undulating slip surface. Gray plastic clays appeared to have been mixed with dark organics by shearing and this zone was extremely mushy and almost soupy in texture. The water content was very high, possibly both due to dilation during shear and low density of the under-consolidated materials.

Organic rich deposits continue to a depth of about 20 feet below the surface while showing an increasing clay and silt content. Most clays are highly plastic with a high water content although there are lenses of lower plasticity clay, silt, and some sand. The variability of grain sizes and other materials is likely due to materials churned up by prehistoric storms. The clays are usually gray in color but vary and are olive, brown, dark gray, and black depending on the type and amount of organic content. Some organic matter towards the base of this deposit was likely roots that grew down through the pre-existing clays and silts or tree debris and that were mixed by prior hurricanes. Some woody debris came up relatively free of clays and closely resembled cypress mulch sold commercially for landscaping purposes. Full recoveries of material in this zone were rarely achieved in this organic rich zone. It appears that the low-density nature (less than water) of these soils caused them to compress due to sampling disturbances.

Most material below 21 feet was gray plastic clay varying from soft to firm and nearly pure lacustrine in origin. This clay included many silt lenses which tended to be stiffer and had some organics at 26 feet. It is likely that the silt and organics were washed into an otherwise quiet prehistoric Lake Pontchartrain by storms.

Sand and broken shells showed up at 30 feet in depth and continued to increase in quantity and size until 35.5 feet when the material became dirty sand with very little cohesion. This hole was terminated at 36 feet. These sands appears to be the Pine Island Beach Trend deposits, described in Section 3.1.3.

The geologic conditions beneath the 17 Street Canal breach are shown in Figures 3.17 thru 3.20. Figure 3.17 shows the relative positions of the cross sections presented in Figures 3.18 and 3.19. Figure 3.18 is a geologic section through the 17th Street Canal breach, extending into the canal. It was constructed using Brunton Compass and tape techniques commonly employed in engineering geology (Compton, 1962). In this section the landside of the eastern levee embankment translated laterally about 48 feet. The levee had two identifiable fill horizons, separated by a thin layer of shells, likely used to pave the old levee crest or the road next to the levee prior to 1915 (similar to the conditions depicted in Figure 4.18). A distinctive basal rupture surface was encountered in al the exploratory borings, as depicted in Figures 3.18 and 3.19. This rupture surface was characterized by the abrupt truncation of organic materials, including cypress branches up to two inches in diameter (shown in the inset of Figure 3.18). The rupture surface was between ¾ and 1 inch thick, and generally exhibited a very high water content (measured as 279% in samples recovered and tested). This material had a liquid consistency with zero appreciable shear strength. It could only be sampled within more competent materials in the Shelby Tubes. A brecciated zone three to four inches thick was observed in samples immediately above the rupture surface. This contained chunks of clay with contrasting color to the matrix materials, and up to several inches across, along with severed organic materials.

The geologic cross section portrayed in Figure 3.19 was taken on the north side of the same lot, using the same Brunton Compass and tape technique. It was located between 80 and 100 feet north of the previous section described above, as shown in Figure 3.17. In this location the landside of the levee embankment translated about 52 feet laterally, to the east. These offsets were based on tape measurement made from the chain link right-of-way fences along the levee crest. No less than four distinct thrust planes were identified in the field, suggesting a planar, translational failure mode, as sketched in the cross section. As with the previous section, the old swamp deposits are noticeably compressed beneath the levee embankment, likely due to fill surcharge and the fact that the drainage canals have never been drained over their lifetime (in this case, since 1858 or thereabouts, described in Section 4.6). This local differential settlement causes the contact between the swamp deposits and the underlying lacustrine clays to dip northerly, towards the sheetpile tips supporting the concrete I-walls constructed in 1993-94. There was ample physical evidence that extremely high pre pressures likely developed during failure and translation of the levee block, in the form of extruded bivalve shells littering the ground surface at the second toe thrust, as shown in Figure 3.20 and indicated on the cross section (Figure 3.19).

Figure 3.17: Aerial photo of the 17th Street Canal breach site before the failure of August 29, 2005. The yellow lines (at middle right) indicate the positions of the geologic sections presented in Figures 3.17 and 3.18, while cross sections A-C' are shown in Figure 3.21.

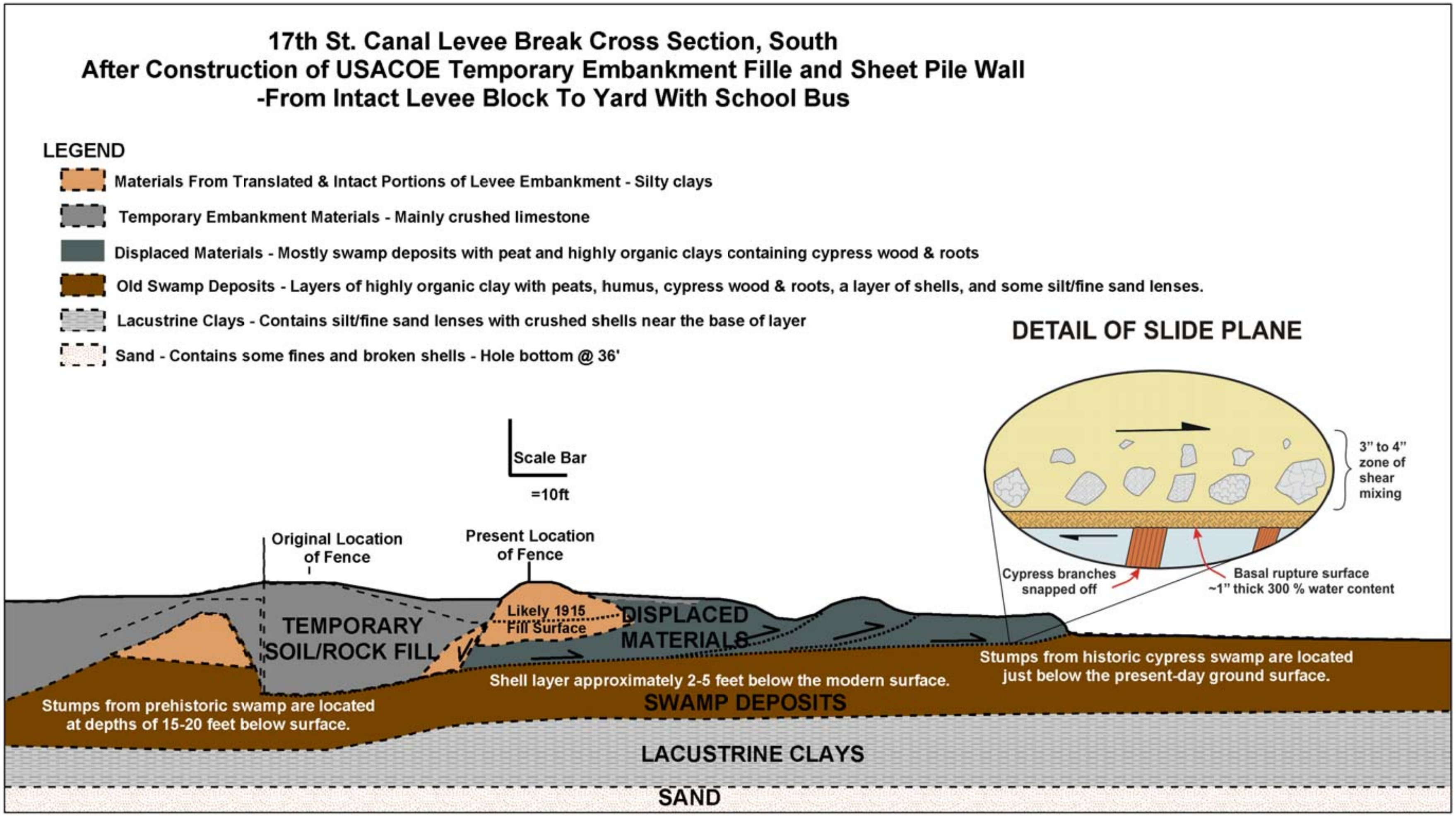

Figure 3.18: West-to-east geologic cross section through the 17th Street Canal failure approximately 60 feet north of the northern curb of Spencer Avenue, close to the yellow school bus. A detailed sketch of the basal rupture surface is sketched above right. The slip surface was about one inch thick with an extremely high moisture content (watery ooze). A zone of brecciation 3 to 4 inches thick was above this. Numerous pieces of cypress wood, up to 2 inches diameter, were sheared off along the basal rupture surface.

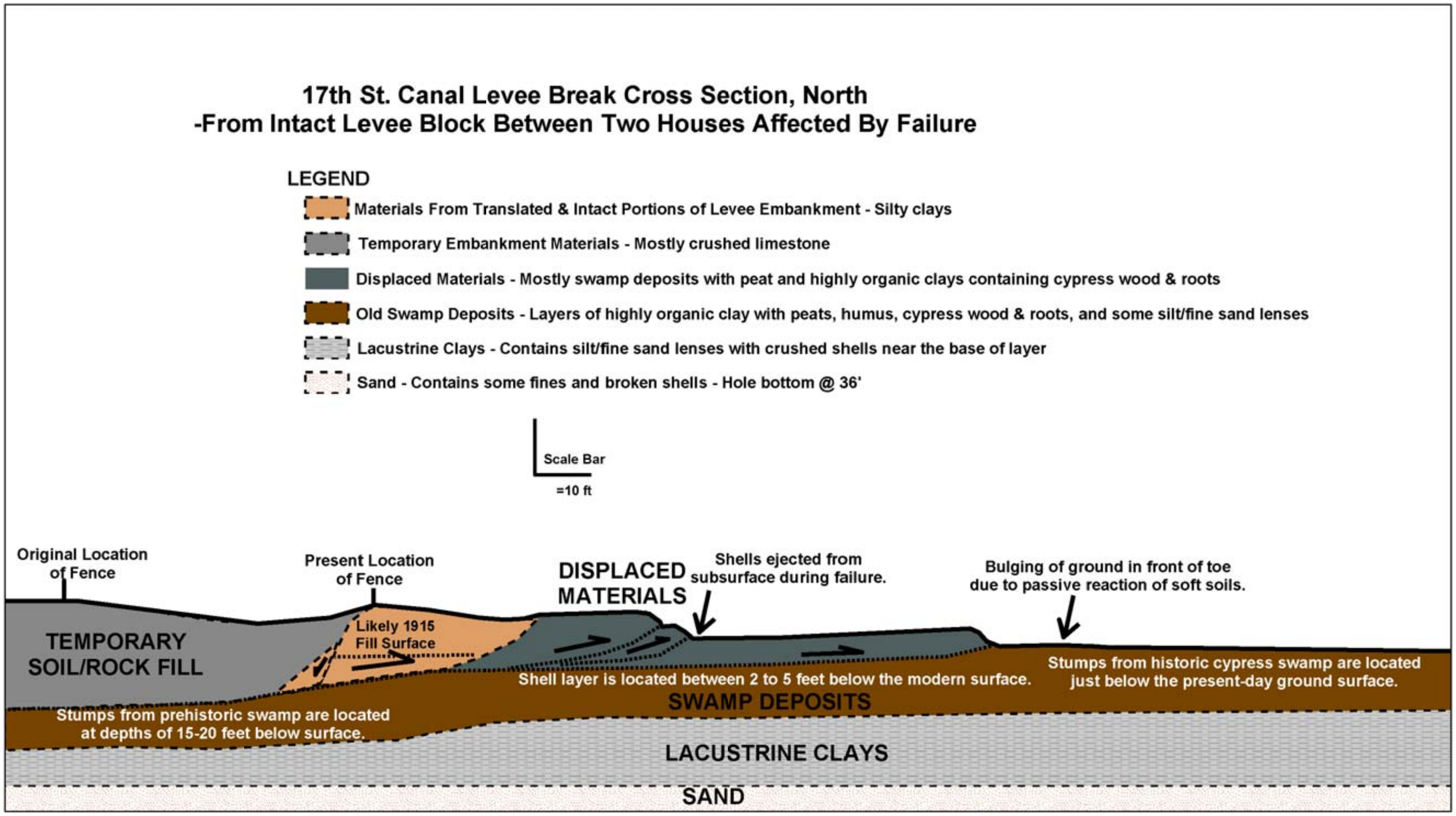

Figure 3.19: West-to-east geologic cross section through the 17th Street Canal failure approximately 140 feet north of the northern curb of Spencer Avenue, just north of the first surviving home next to the canal. Large quantities of bivalve shells were extruded by high water pressure along the regressing toe thrusts (shown in Figure 3.20). Note the slight back rotation of the distal thrust block.

Figure 3.20: Bivalve shells ejected by high pore pressures emanating from toe thrusts on landside of failed levee at the 17 Street Canal (detail view at upper left). These came from a distinctive horizon at a depth of 2 to 5 feet below the pre-failure grade (photo by C.M. Watkins).

Planar translational failures are typical of situations where shear translation occurs along discrete and semi-continuous low strength horizons (Cruden and Varnes, 1996). Additional evidence of translation is the relatively intact and un-dilated nature of the landside of the failed levee embankment, upon which the old chain link right-of-fence was preserved, as well as a substantial portion of the access road which ran along the levee crest, next to the concrete I-wall. Wherever we observed the displaced concrete I-wall in this area it was solidly attached to the Hoesch 12 steel sheetpiles, each segment of which was about 23 inches wide (as measured along the wall alignment) and 11 inches deep, with an open Z-pattern. The thickness of the sheets were about 7/16ths of an inch. The observed sheetpiles interlocks were all attached to one another. The entire wall system was quite stiff and fell backward (towards the canal) *after* translating approximately the same distance as the landslide of the levee embankment. The sheetpiles and attached I-walls formed a stiff rigid element. The sheetpiles were 23 ft-6 inches long and were embedded approximately 2 to 3 feet into the footings of concrete I-walls.

The geology of the opposite (west) bank was relatively similar except that the organics persist in large quantities, to a depth of 36 feet. The marsh deposits appeared deeper here and root tracks filled with soft secondary interstitial clay persisted to a depth of 39 feet. Sand and shells were first encountered at 40 feet and cohesionless send was found at 41 feet. This hole was terminated at 42 feet.

3.2.3 Interpretation of data from CPT Soundings

Six distinctive geologic formations are identified studying the Cone Penetrometer Test (CPT) soundings which were done in the vicinity of 17th Street Canal: Fill, swamp/marsh deposits, Intermixing deposits, lacustrine deposits, Pine Island beach sand deposits and Bay Sound deposits. The description and coverage of these geologic formations from CPT soundings are explained in the following paragraphs. These unit assignments are shown graphically in Figure 3.21.

FILL: Fill is not present in all CPT soundings. It is characterized *by stiff silty clay to sandy clay and sandy silt with some silt lenses.* It is differentiated from the swamp deposits by having little or no organic matter in its content. Along the breached area, the fill appears to be missing in the CPT soundings. Fill thickness is around 10 ft (down to -8 ft below sea level) on the west bank of the 17th street Canal. Just north of the breached area (east bank), the thickness of the fill ranges from 14 ft to 16 ft (down to -10 ft). Fill materials for the drainage canals appear to have been placed in three sequences: 1) during the original excavation of the various canals, between 1833-1878; 2) after the 1915 Grand Isle Hurricane; and 3) after the October 1947 hurricane (the history of the drainage canals is described in Chapter 4, Section 4.6).

SWAMP/MARSH DEPOSITS: Marsh deposits consists of *soft clays, organic clays usually associated with organic material (wood and roots)*. The organic materials are readily identifiable by observing the big jumps in the friction ratios of the CPT's. The thickness of swamp/marsh deposits is around 9.5 ft on the west bank of the canal and 4 to 6 ft on the east bank of the canal. The depth at which swamp/marsh deposits encountered on banks ranges from approximately -8.5' (on the west side) to -10' (on the east side), using the NAVDD882004.65 datum.

INTERMIXING ZONE: This zone consists of mixture of *soft clays, silt lenses with little or no organic material*. The thickness of intermixing zone ranges from 3 ft to 8.5 ft on the east bank of the canal. No intermixing zone is interpreted on the west bank of the canal. However the contact between marsh and intermixing zone is highly irregular and should be correlated with borehole data.

LACUSTRINE DEPOSITS: Lacustrine deposits consist of *clays to organic clays with thin silt and fine sand lenses*. *No organic matter* is found in these deposits. The thickness of lacustrine deposits is around 17-19 ft on the west bank of the canal and 15-22 ft on the east bank of the canal. The depth at which lacustrine deposits encountered ranges from -17 (on the west side) to 14-23 (on the east side).

PINE ISLAND BEACH TREND SANDS: Beach sand is identified by its *sand and silty sand* content. It is easily recognized in the CPTs by a large jump in the tip resistance and a drop in the pore pressure. The depth at which beach sand encountered ranges from -37 (on the west side) to -36 ft (on the east side) and it has fairly uniform 6 ft of thickness.

BAY SOUND: This deposit contains *stiff organic clays and stiff clays*. It is easily recognized in the CPTs by a large drop in the tip resistance and an increase in the pore pressure. Bay sound deposits are only encountered on the east side of the canal and only top

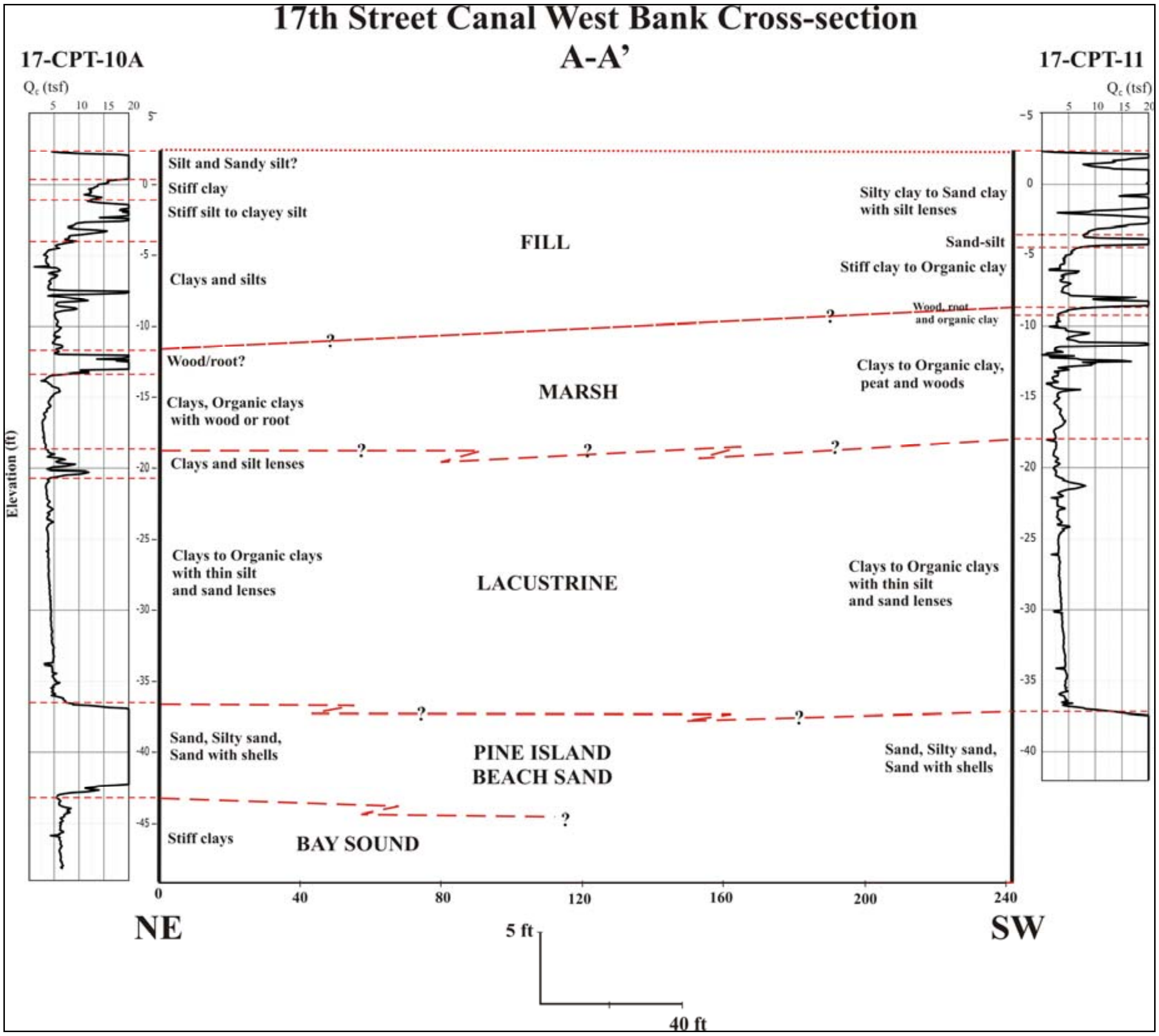

Figure 3.21 - upper: Stratigraphic interpretations between CPT soundings along western embankment of the 17th Canal (in Jefferson Parish), opposite the breach on the east side. The marsh-swamp deposits are dipping slightly towards Lake Pontchartrain, while the lacustrine clays appear to be flat lying.

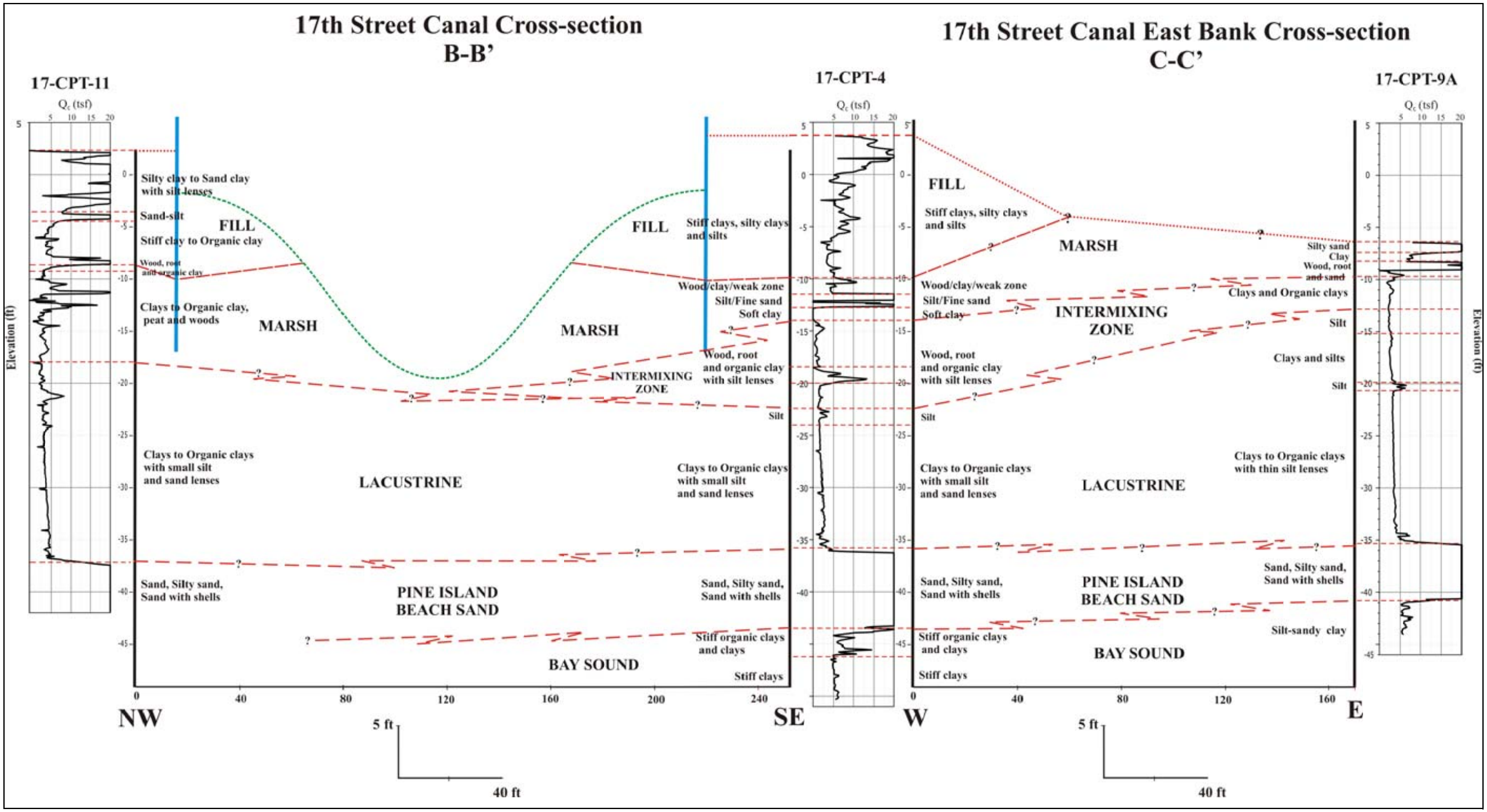

Figure 3.21- lower: Stratigraphic interpretations and cross-canal correlations in vicinity of the 17th Street Canal breach on August 29, 2005. The swamp much appeared to be thinning northerly, as does the underlying Pine Island Beach Trend. The lacustrine clays appear to thicken northward, as shown. The approximate positions of the flood walls (light blue) and canal bottom (dashed green) are indicated, based on information provided by the Corps of Engineers (IPET, 2006).

of bay sound deposits encountered in this area –not bottom. The depth at which these deposits encountered is around -42 ft (which appears to be uniform in this area).

3.3 Geologic Conditions at London Avenue Canal (North) Breach

3.3.1 Introduction

The London Ave. Outlet Canal Levee system catastrophically failed on its western bank just south of Robert E. Lee Blvd. during Hurricane Katrina between 9 and 10 AM on August 29, 2005. The hurricane induced a storm surge from the Gulf of Mexico that moved into Lake Pontchartrain and subsequently backed up into the canal. The levee failed in two locations by translating laterally atop poor foundation materials, not by overtopping. One break formed on the west bank levee just south of Robert E. Lee Blvd. The toe of this break appears to have thrust over the surrounding landscape 6-8 feet in places.

The east bank levee directly opposite this break translated by about two feet, but did not breach catastrophically. An imminent failure was likely but hydrostatic pressure was relieved by the break opposite this bank and a break on the east bank further south near Mirabeau Ave. Floodwall panels here have been displaced, tilted, and distressed

Cohesionless beach sands from the micaceous Pine Island beach strand comprise the majority of the deposits beneath the London Ave. Canal Levee. These sands were quickly eroded and deposited in great quantities in the neighborhoods surrounding the breaks. Much of the sand was also likely in the bottom of the canal prior to the breaks.

3.3.2 Geology beneath the levees

A series of continuously sampled borings was conducted and logged using 3-inch Shelby tubes where cohesive soil was present. Cohesionless sands were sampled using the material recovered during the Standard Penetration Tests (SPT). CPTs were conducted alongside many of the other borings.

The first two feet of material appeared to be topsoil heavily influenced by modern vegetative growth. The material was a dark brown silty clay with many roots and organics and a relatively low water content.

The next 0.65 feet contained highly plastic and water-rich organic clay and contained what appeared to be the slide plane at 2.65 feet in depth. Although the slip surface was likely deeper under the levee, it was thrusting to the surface at this point. There was a return to the dark brown organic silty clay at this point, which continued to 3.1 feet where there was a strong contact. A gray clayey sand remained in the last 0.5 feet of the tube.

From 4-6 feet appeared to be a deposit of shallow marsh materials transitioning to beach sands from Lake Pontchartrain. The first part of the tube contained gray organic rich clays and silts with a fetid odor and transitioned to a relatively clay gray sand. Cohesion dropped beyond 6 feet in depth and sampling was no longer possible using a Shelby tube. Sampling continued using an SPT split spoon sampler down to 44 feet where clays were again encountered. The entire layer of sand appeared to be beach sand. Shells were included throughout the layer and most sand was mica rich, likely brought in by long shore drift from the Pearl River. Shells were included throughout the layer and most sand was mica rich, likely transported by longshore drift from the Pearl River. This is the "relic beach" of the Pine Island Beach Trend described in Section 3.1.3.

The clay recovered from 44-46 feet was, silty, blue-gray in color, and very plastic. Sand and shell fragments were mixed in with this clay, possibly due to wave action and mixing due to storms. Additional boring logs show a lacustrine bay sound material at this depth. No sampling was conducted by our team below this depth. All recovered sediment was Holocene in age.

Boring logs from Design Manual 19A (U.S. Army Corps of Engineers, 1984) show similar results. In addition, the transitional layer of clayey sand is shown beneath the breach but not below adjacent unfailed sections of the levee. The marsh deposits and transitional zone extend up to 10 feet deeper beneath the breached levee (west) and distressed levee (east) than below the unbroken portions of the levee. Marsh deposits begin near the surface and transition to sand at around 10-15 feet in depth. The sand continues to around 45 feet where lacustrine bay sound material is found. This continues down to Pleistocene materials at 65-75 feet.

3.4 Geologic Conditions at London Avenue (South) Canal Breach

3.4.1 Introduction

The London Ave. Outlet Canal levee system catastrophically failed on its eastern bank just north of Mirabeau Ave. during Hurricane Katrina between 7 and 8 AM on August 29, 2005. This failure appears to have been induced by concentrated zone of underseepage, because the failure was relatively deep, and did not extend over a long zone of the canal. Nor was there any physical evidence of overtopping. The seepage appears to have been driven by high water level in the canal, caused by the storm surge coming up the canal from its mouth along Lake Pontchartrain.

Post failure reconnaissance revealed that micaceous sands from the Pine Island Beach Strand were eroded from this breach and, possibly, from within the canal where they were deposited throughout the surrounding neighborhood.

3.4.2 Geology beneath the levees

The section of levee incorporated in the London South breach is founded upon geology similar to the northern London Ave. Canal failure. The levee was constructed upon approximately ten feet of organic-rich cypress swamp deposits. Borings by the Corps of Engineers indicate that the swamp deposits extended three to five feet deeper below the failure area than the areas immediately adjacent to the breach (north or south of it). Unlike the London Avenue northern breach, where there is a transition of clayey sand between the marsh deposits and the underlying Pine Island Trend sands, there is a more definite transition at this location. These differences in foundation conditions are indicated on the boring logs within Design Manual 19A (U.S. Army Corps of Engineers, 1984).

3.5 Geologic Conditions along the Inner Harbor Navigation Canal

3.5.1 Introduction

Levees surrounding the Inner Harbor Navigation Canal (IHNC) were overtopped and breached catastrophically during Hurricane Katrina. Some of New Orleans' worst devastation occurred at two large breaches on the east side of the IHNC in the Lower Ninth Ward. These breaches washed houses from their foundations, leaving many blocks of the neighborhood as little more than piles of used lumber, destroyed automobiles, and other debris. Although the primary mode of failure at this site was land-side scour caused by overtopping, some translation of the embankments atop their foundations appears to have occurred.

3.5.2 Geology

The geology beneath the IHNC levees is far more complex and variable than that of the foundation materials at the London Ave. and 17th St. Canals. The foundation materials here tend to be fluvially dominated by past distributaries of the Mississippi River with the exception of the area near Lake Pontchartrain. Conditions near the lake more resemble those under the London Ave. Canal but with a slightly thicker marsh deposit. The buried beach deposit is present below the marsh and eventually transitions into prodelta clays.

As with most modern fluvial systems, the geology of this Holocene deposit is complex and varies widely in both vertical and horizontal extent. The area was once covered by the marshes and swamps once common to the area. Organic fat clays are dominant and contain peat and other organic materials. Some wood is present but not in the quantities found at the 17th St. Canal site, indicating that marshes were more pronounced at this location. These deposits vary in thickness between 10-20 feet, depending on the location.

Interdistributary materials consisting largely of fat clays dominate much of the IHNC geology below the marsh deposits. This layer, which also contains zones/lenses of lean clays and silt, is approximately 30-35 feet thick.

A complex estuarine deposit exists below the interdistributary layer and is comprised of a complex mix of clays, silts, sands, and broken shell material. This deposit is about 30 feet thick and is underlain by Pleistocene deposits (undifferentiated, but commonly a stiff clay). Cross sections from The New Orleans District's Design Manual 02 Supplement 8 (U.S. Army Corps of Engineers, 1968, 1969, 1971) do not always do a good job of differentiating this material, but much of the material appears to be sand mixed with clays and silts. These deposits lie at sufficient depth as to preclude their having any significant impact on levee stability.

Abandoned distributaries cut across the IHNC in some locations. Materials in the old channels are highly variable. Although basal units usually consist of sands, upper units are heterogeneous layers of silts, clays, sandy silts, and silty sands. Natural levee deposits are commonly found around these old channels.

3.6 Paleontology and Age Dating

3.6.1 Introduction

Micropaleontology was used in conjunction with carbon 14 dating to determine both the age and depositional environment of the sediments below levee failure sites in New Orleans, LA. Foraminifera, single-celled protists that secrete a mineralized test or shell, were identified as these organisms grow in brackish or marine settings but not freshwater. Their presence in sediments indicate that they were deposited in-situ or were transported from brackish Lake Pontchartrain or marine environments by Hurricanes. Palynology, the identification and study of organic-walled microfossils, commonly pollens and spores, was conducted to aid in the re-creation of paleoenvironments beneath the levees. Macrofossils of the phylum *Mollusca*, including classes *Gastropoda* and *Bivalvia* are common in sands of the Pine Island Trend (Rowett, 1958). Most recovered samples contained heavily damaged shells or fragments.

3.6.2 Palynology

Although varying sediment types including clays, peats, and sands were studied, similar palynomorphs were found throughout the samples. These samples came from different depths and locations throughout New Orleans. The commonalities between the sediments may be due to transportation of the palynomorphs by wind and water or the mixing of materials by hurricanes. Pollens of the family *Taxodiaceae*, genus *Cupressacites* (cypress) are common. Species of cypress are common in perennially wet areas such as swamps. Cypress is common throughout the swamps of the Gulf Coast Region. Cypress wood, including trunks, roots, and stumps, was unearthed by scour during the levee failures and subsequent construction to temporarily patch the levees. Samples recovered in 3” Shelby tubes commonly included cypress fragments resembling commercially available landscaping mulch and cores of intact wood. Cypress trees are freshwater and die if exposed to salt water for a prolonged amount of time.

Dinocysts/Dinoflagellates were also discovered among the samples taken for palynology. Dinoflagellates are single-celled algae belonging to the Kingdom Protista. They live almost exclusively in marine and brackish water environments, with very few freshwater species. The discovery of these organisms was not surprising, given the close proximity to brackish Lake Pontchartrain (essentially a bay). On the other hand, several exclusively marine species that live in the open ocean were recovered. These species were transported a far distance inland, indicating transport by a catastrophic event, possibly a hurricane storm surge or tsunami.

3.6.3 Foraminifera

Foraminifera were identified in the Pine Island Trend, a micaceous quartz beach sand that was deposited in the Holocene Gulf of Mexico by the Pearl River of Mississippi. This sand was subsequently formed into a large sand spit by long shore drift, separating Lake Pontchartrain from the rest of the Gulf of Mexico (Saucier, 1994). Lake Pontchartrain is a brackish body of water with only a small connection to the Gulf. Agglutinated, planispiral, and uniserial foraminifera were discovered where the sand grades into the silts and clays deposited in the low energy environments of Lake Pontchartrain. Although foraminifera are abundant at these locations, their diversity is low. This is indicative a stressed environment and is not surprising, given the brackish nature of Lake Pontchartrain.

3.6.4 Carbon 14 age dating

We are awaiting the results of six C14 age dating by the NSF-funded age dating laboratory at the University of New Mexico in Albuquerque, NM. These are samples of the cypress wood and fibrous peats recovered at the 17th Street Canal failure area.

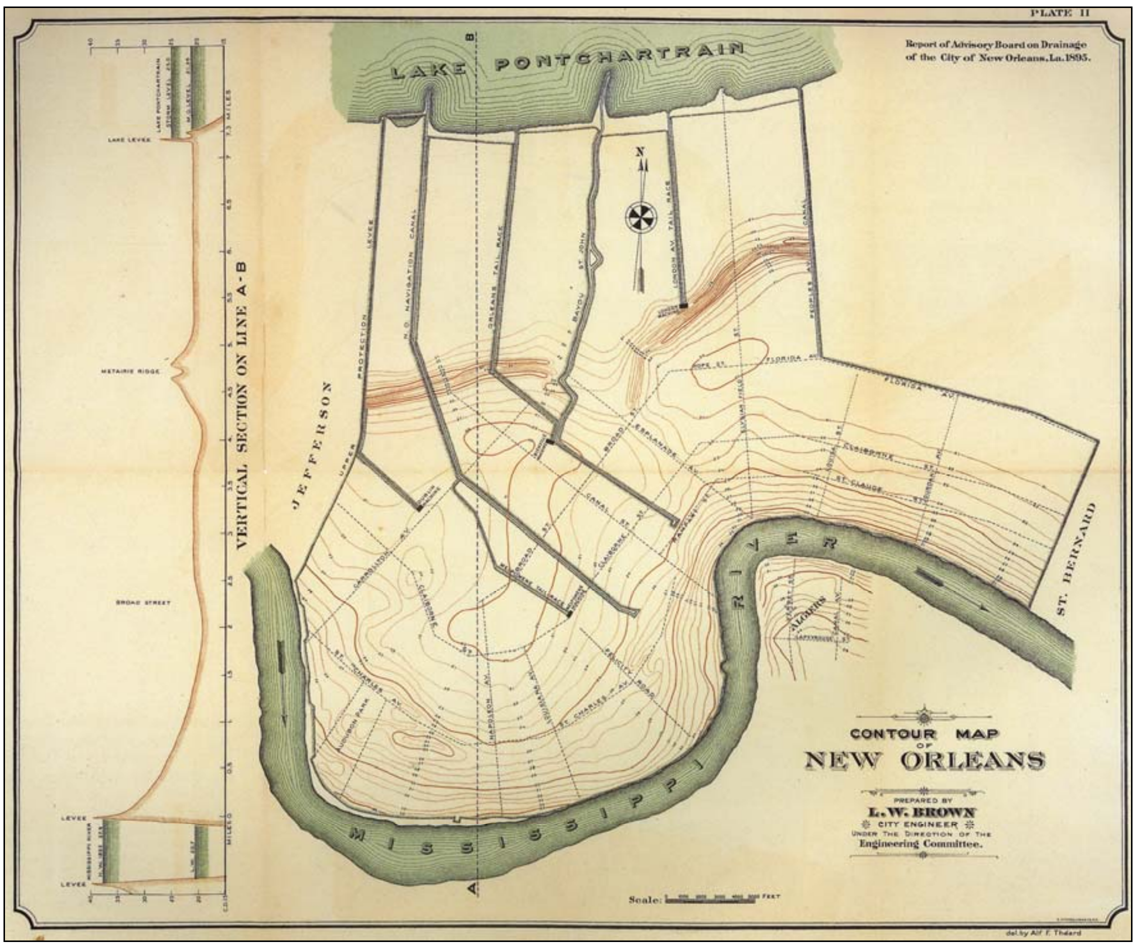

Figure 3.22: Topographic map with one foot contours prepared under the direction of New Orleans City Engineer L.W. Brown in 1895. This map was prepared using the Cairo Datum, which is 21.26 feet above Mean Gulf Level.

3.7 Mechanisms of Ground Settlement and Land Loss in Greater New Orleans

3.7.1 Settlement measurements

URS Consultants (2006) in Baton Rouge recently completed a study for FEMA of the relative ground settlement in New Orleans since 1895, using the Brown (1895) map, which has 1 foot contours ands extended north to the Lake Pontchartrain shoreline. This comparison was made by creating Digital Elevation Models (DEMs) of the 1895 map (Figure 3.22) relative to Mean Gulf Level against the 1999/2002 DEM extracted from LiDAR data and New Orleans network of benchmarks. The resulting product was a map noting relative settlement between 1895 and 1999 (in feet), shown in Figure 3.23. This study suggests that the entire city has settled between 2 and 10 feet. During this same interim, sea level has risen approximately 12 inches. The area with the greatest settlement (> 8 feet) were north of I-610 in the Lakeview area and north of Mirabeau Ave. in the Gentilly area, exclusive of the 1931 fill along Lake Pontchartrain (which extends a half mile into the Lake).

3.7.2 Tectonic Subsidence

Tectonic subsidence is caused by sediment compaction at great depths (Figure 3.24). Salt and muds flow towards the continental shelf. Pressure ridges and fold belts develop; which are akin to sitting on a peanut butter and jelly sandwich and watching material ooze out and shift. The Continental Slope and Shelf is blanketed by large subaqueous landslides.

3.7.3 Lystric Growth Faults

As compacting materials move seaward, the ground surface drops. If sediment is not added at the ground surface, the seaward side of these features gradually subsides below sea level. The delta's lystric growth faults have been grouped into bands thought to be more or less related to one another. The relatively recent emergence of the Baton Rouge Fault Zone along the northern shore of Lake Pontchartrain, thence towards Baton Rouge, is the most striking example, and one of the furthest inland (Figures 3.25 and 3.26).

3.7.4 Compaction of Surficial Organic Swamp and Marsh Deposits

The interdistributary sediment package covering the old back swamps around New Orleans are highly compressible and the neighborhoods built on these materials exhibit obvious signs of differential settlement. This is particularly true of the West End, Lakeview, City Park, Fillmore, St. Anthony, Dillard, Milneburg, Pontchartrain Park, Desire, and Gentilly neighborhoods flanking Lake Pontchartrain. Most of this settlement is ascribable to oxidation-induced settlement of underlying peaty soils, caused by local drawdown of the ground water table, as sketched in Figure 3.27. The amount of post-development settlement is more-or-les proportional to the thickness of the peaty surface layer, shown in Figure 3.12. It varies in thickness from a few feet to as much as 20 feet, depending on location (WPA-LA, 1937; Kolb and Saucier, 1982).

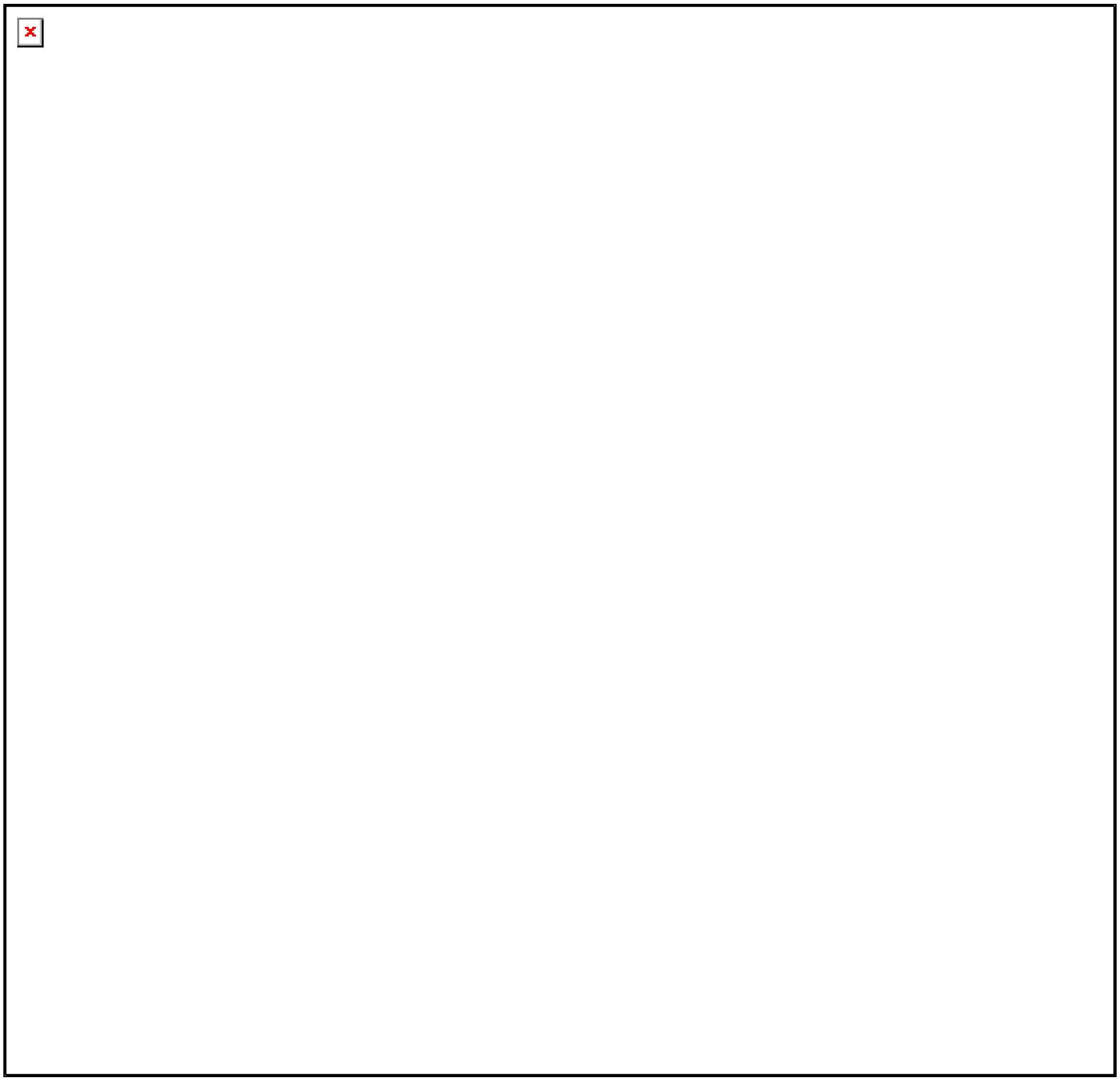

Figure 3.23: Map showing relative elevation change between 1895 and 1999/2002, taken from URS (2006). The approximate net subsidence was between 2 and 10+ feet, depending on location. The brown colored zones along Lake Pontchartrain and the Mississippi River are areas where substantive fill was placed during the same interim.

The mechanisms promoting surficial settlement in lower New Orleans are thought to be: 1) drainage of the near surface soils, through simple near-surface dewatering and the storm water collection system; and 2) biochemical oxidation of organic materials above the [lowered] water table. Simple drainage of the surficial peaty soils can induced consolidation of up to 75% of their original thickness (Kolb and Saucier, 1982), which in of itself, could account for up to 12 ft of settlement, if the local water table was lowered >15 feet. But, biochemical oxidation continues afterwards, with greater severity during extended periods of drought, as occurred in the late 1990s-early 2000s around New Orleans. Oxidation continues until only the mineral constituents of the soil are left remaining.

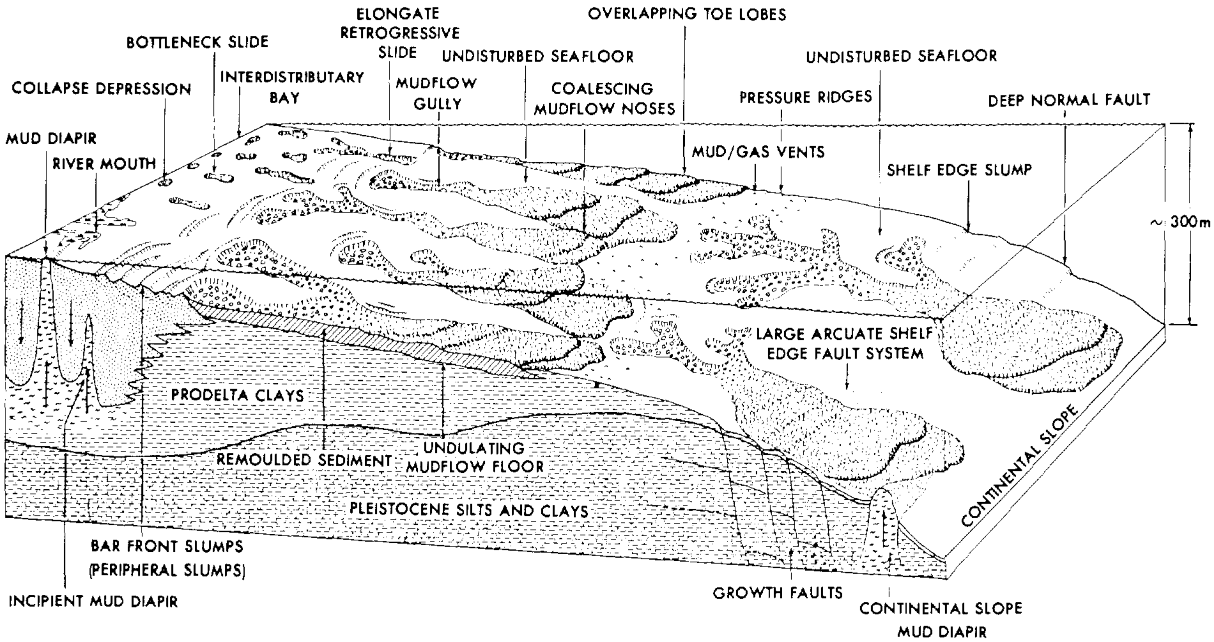

Figure 3.24: Block diagram illustrating various types of subaqueous sediment instabilities in the Mississippi River Delta, taken from Coleman (1988).

Dense urban development also leads to increased subsidence because the absorptive capacity of the peaty soils is decreased by the mass implementation of impervious surfaces, such as streets, parking lots, sidewalks, roofs, driveways, etc. Increasing the area of impervious surfaces decreases overall seasonal infiltration and increases the peak runoff through hardened impervious surfaces. As a consequence, the Sewerage & Water Board of New Orleans had to continually increase the capacity of their drainage collection, conveyance and discharge system during the post-1945 period. These examples are from the Lakeview area adjacent to the 17th St. Canal failure, where the ground appears to have settled 10 to 16 inches since 1956.

The Lakeview and Gentilly neighborhoods were intensely developed in the post World War II era, mostly between 1946-70 (although infilling of newer structures continued up through 2005, as older structures were torn down). Most residential structures built in lower New Orleans after the mid-1950s are concrete slabs founded on wood pilings 6 to 8 inches in diameter, driven about 30 feet deep (Waters, 1984). From inspection, it appears that the ground beneath the foundations has settled 10 to 40 inches over the past 50 +/- years since these homes were constructed. This development was accompanied by a lowering of the ground water table to accommodate normal living conditions and combat mildew and mold in the crawl spaces beneath the homes (Figure 3.28 - upper). Since the historic groundwater table was at or within a few inches of the ground surface in this area, the lowering of the water table by 2 to 10 feet in this area hastened near-surface settlement through oxidation of the organic rich peat soils underlying the area.

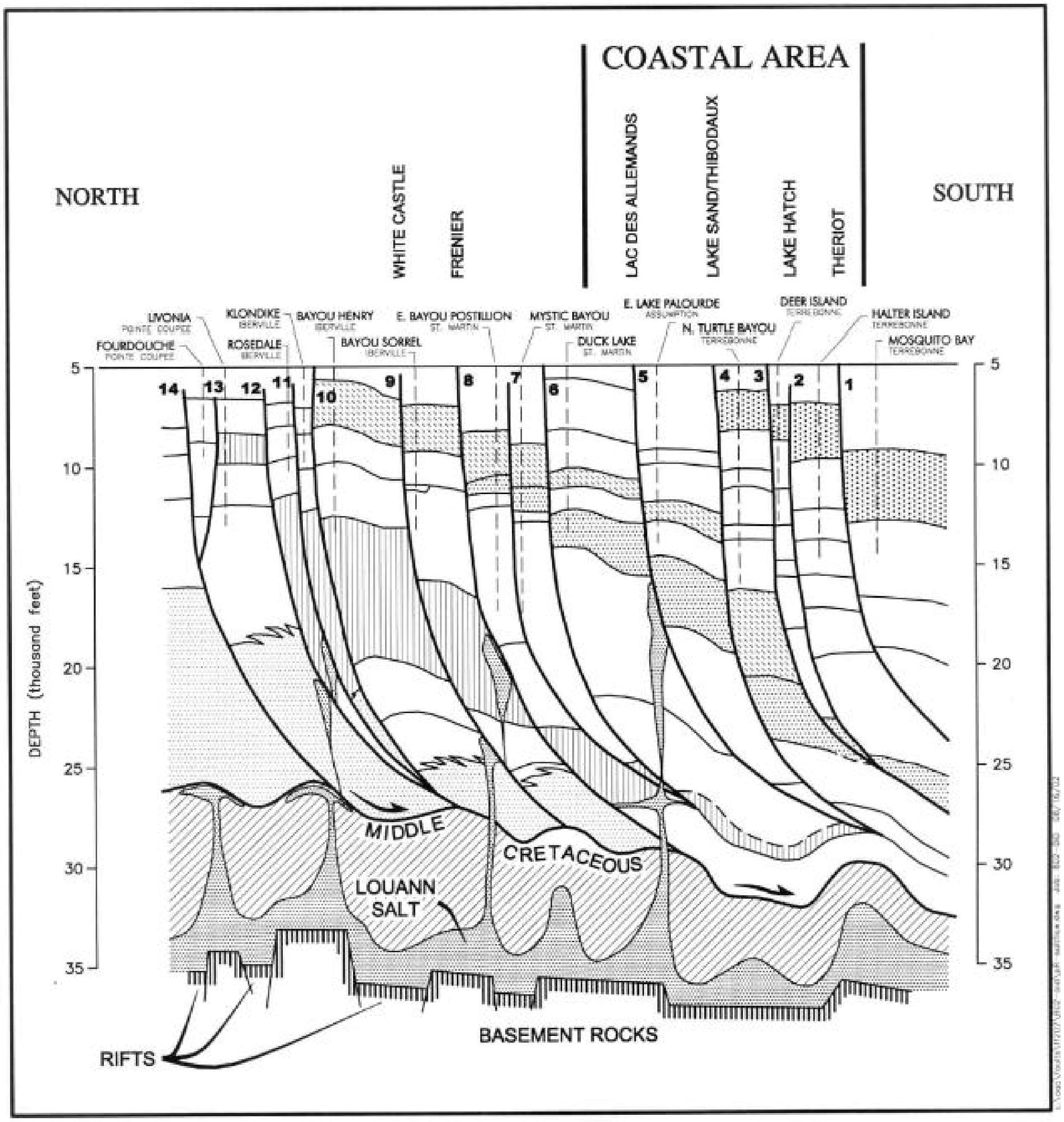

Figure 3.25: Geologic cross section through the Gulf Coast Salt Dome Basin, taken from Adams (1997). This shows the retrogressive character of young lystric normal faults cutting coastal Louisiana, from north to south. The faults foot in a basement-salt-decollement surface of middle Cretaceous age (> 100 Ma).

As the peats oxidized, the ground settles, creating a depressed area beneath pile supported homes (Figure 3.28-upper). Groundwater pumping, drainage, and structural and earthen surcharges all contribute to the observed settlement. Historic measurements of ground settlement in the Kenner area of Jefferson Parish are shown in Figure 3.29.

During this 130 to 170 years since the drainage canals were constructed upon what became the Lakeview and Gentilly areas, these channels have never been drained for any significant period of time, because they were open to Lake Pontchartrain. As a consequence, the peaty soils immediately beneath these canals (17^{th} Street, Orleans, and London Avenue) and Bayou St. John have not experienced significant near-surface settlements like those fomented by oxidation of peaty soils in the adjoining neighborhoods, although they have experienced gross ground settlement due to the other causes described in Section 3.7.

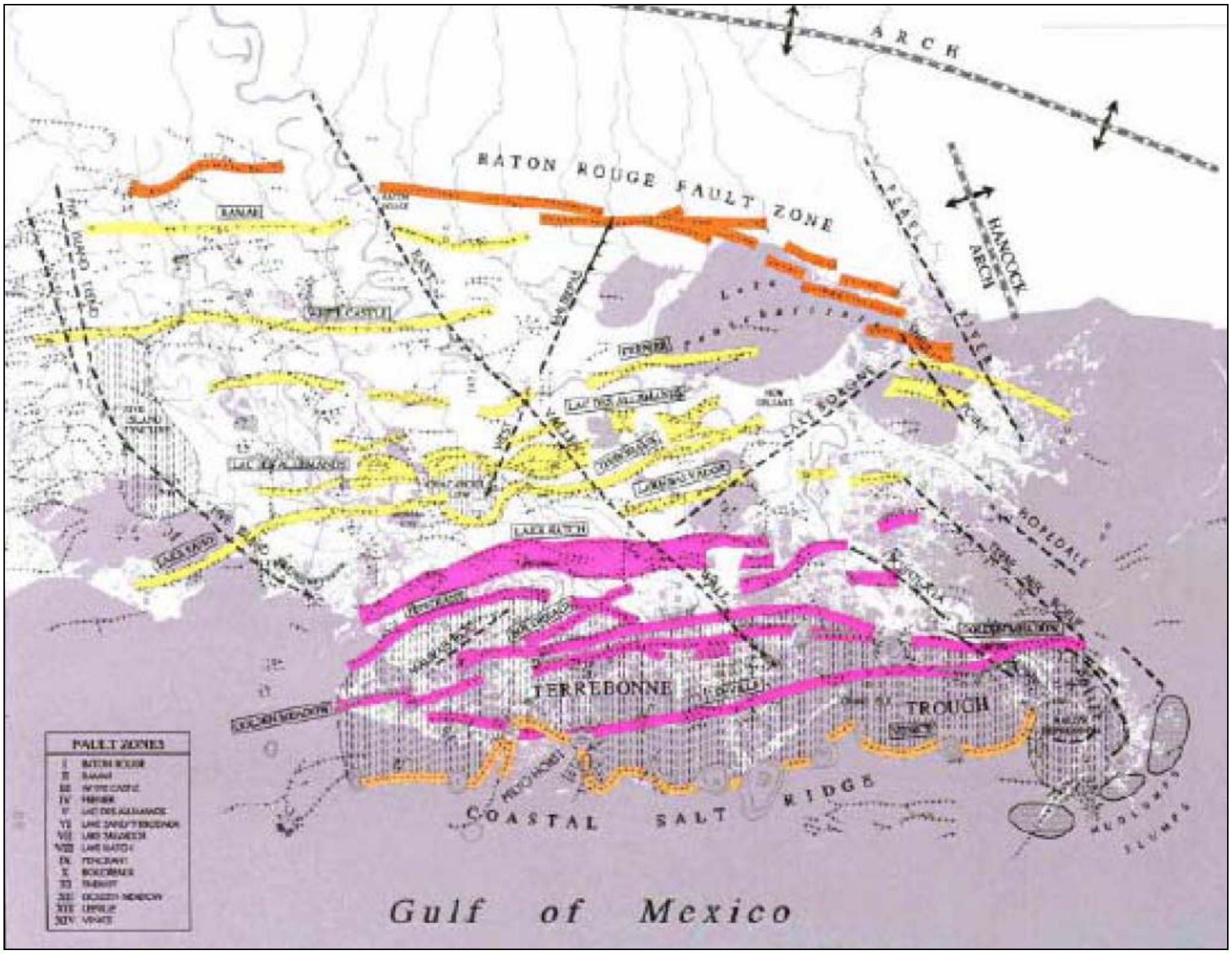

Figure 3.26: Structural geologic framework of southeastern Louisiana, taken from Coastal Environments (2001). This plot illustrates the en-echelon belts of growth faults forming more or less parallel to the depressed coastline. The Baton Rouge Fault Zone (shown in orange) is graphic fault scarp feature that has emerged over the past 50 years, north and west of Lake Pontchartrain.

This history of near-continual ground settlement necessitated raising of the old drainage canal embankments on three occasions in the 20th Century, following hurricane-induced flooding from storm surges off Lake Pontchartrain, in: 1915, 1947, and 1965. Earth fill was placed upon the levee embankments in 1915 and 1947. After flooding associated with Hurricane Betsy in 1965 steel sheetpiles were used in selective zones to increase the freeboard for Category 3 storm surge (a figure that shifts each decade, as new information and models are developed). In the 1990s sheetpile–supported concrete I-walls wee constructed along the crests of the drainage canals and on either side of the IHNC.

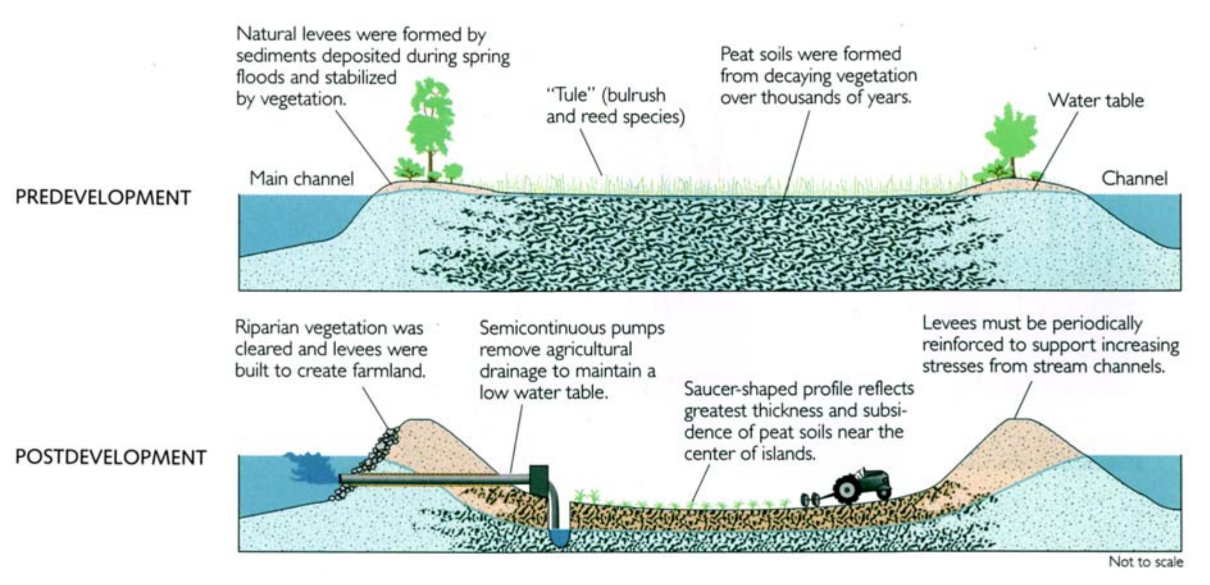

Figure 3.27: Settlement of surficial peaty soils is usually triggered by lowering of the local groundwater table, either for agriculture or urban development. Lowering the water table increases the effective stress on underlying sediments and hastens rapid oxidation of organic materials, causing settlement of these surficial soils (taken from AIPG, 1993).

3.7.5 Structural Surcharging

An interesting aspect of the recent URS (2006) study for FEMA is the marked increase in settlement noted in the Central Business District, where tall structures are founded on deep piles. This area settled 5 inches in 100 years, but much less further away from the city's tallest and heaviest structures. The sandy natural levees along the Mississippi River even settled 2 inches; likely due to surcharging by the Corps' Mississippi River & Tributaries Project (MR&T) sequences of levee enlargements, between 1928-60.

3.7.6 Extraction of Oil, Gas, and Water

Since the 1960s groundwater withdrawal has been recognized as contributing to subsidence of the Gulf Coast area, especially adjacent to deep withdrawal points for industrial consumption (Kazmann and Heath, 1968). More recently, R.A. Morton of the USGS has blamed oil and gas extraction for the subsidence of the Mississippi Delta. Morton has constructed convincing correlations between petroleum withdrawal and settlement rates on the southern fringes of the delta, near the mouth of the Mississippi River (Morton, Buster, and Krohn, 2002). But, other factors are likely involved as well, as petroleum withdrawal alone cannot account for marked settlement well inland of Lake Pontchartrain, where little withdrawal has occurred. Figure 3.30 presents Saucier's (1994) map of the Mississippi Delta, which summarizes the structural geologic framework of the area. This shows salt basins, salt domes, and active growth faults that pervade the delta region. Solutioning of salt diapirs and seaward migration of low density contrast materials likely exacerbate settlement, but more slowly that fluid/gas withdrawal.

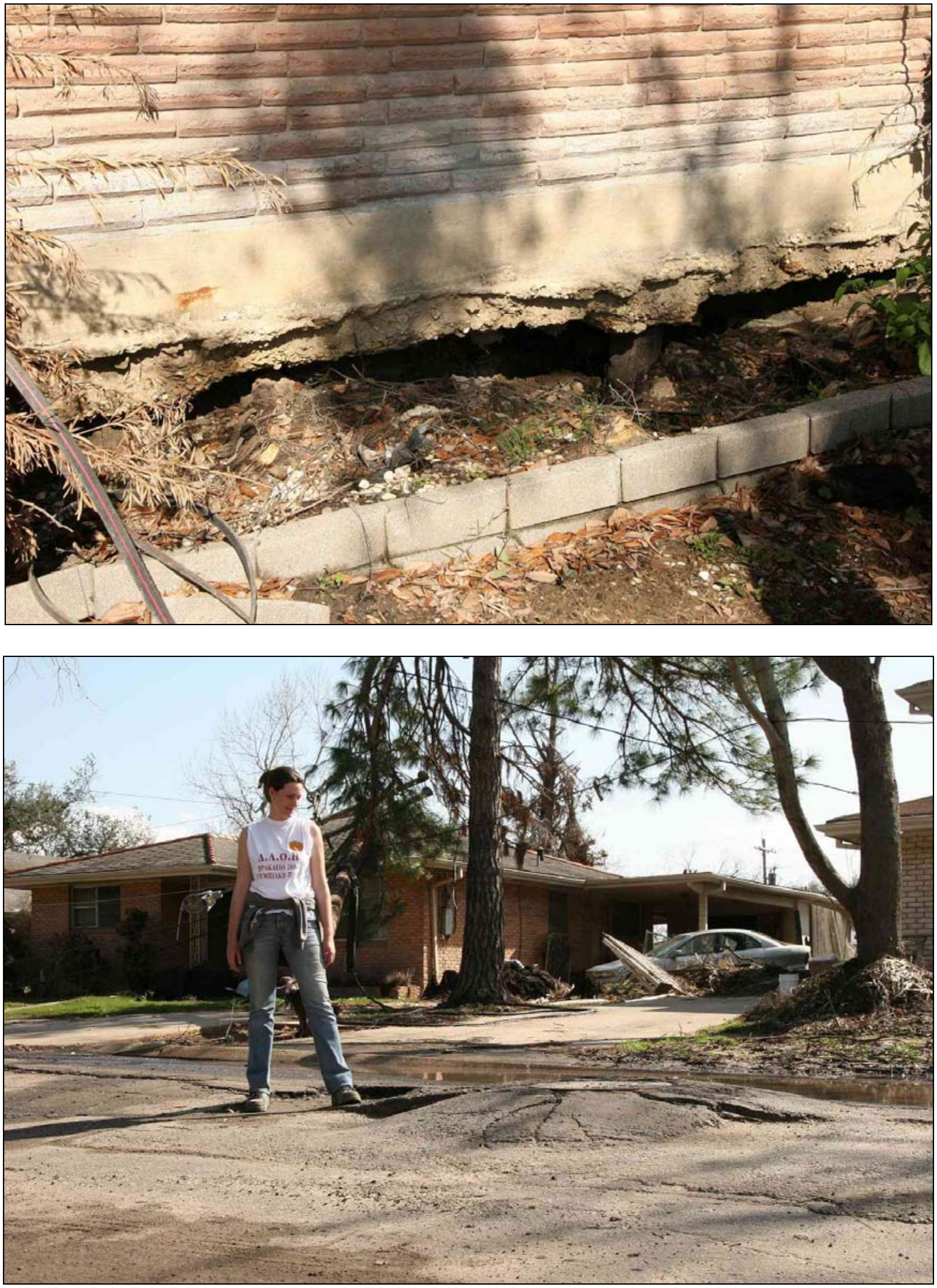

Figure 3.28: Upper photo shows gross near-surface settlement of homes in the Lakeview neighborhood, close to the 17th Street Canal breach. Most of the homes were constructed from 1956-75 and are founded on wood piles about 30 feet deep. The lower photo shows protrusion of a brick-lined manhole on Spencer Avenue, suggestive of at least 12 inches of near surface settlement during the same interim (photos by J. D. Rogers).

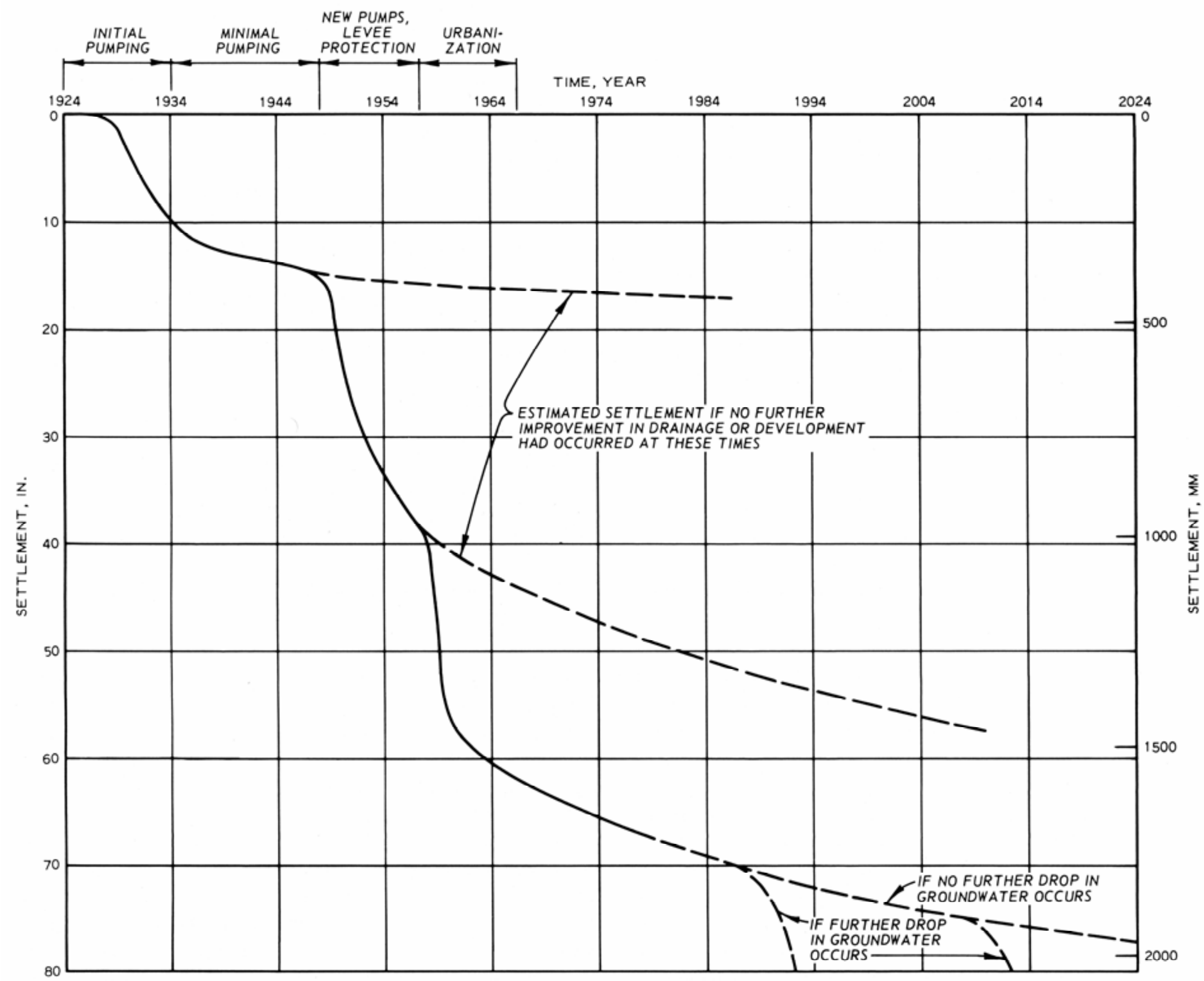

Figure 3.29: Record of historic settlement in the town of Kenner, which is characterized by 6.5 to 8 feet of surficial peaty soils (taken from Kolb and Saucier, 1982). The earlier episodes of settlement were triggered by groundwater withdrawal (for industrial and municipal usage), while the later episode was caused by drainage associated with urban development. This area was covered by dense cypress swamps prior to development.

3.7.7 Coastal Land Loss

The U.S. Geological Survey's National Wetlands Research Center (USGS-NWRC) has about 100 years of land loss information. Since 1973, satellites have allowed monitoring of sediment expulsion from the delta and the nefarious shoreline, which is continuously sinking. The USGS-NWRC has been monitoring coastal land loss over the past 50 years using 1956 and 1978 imagery published by Cahoon and Groat (1990) and LANDSAT Thematic Mapper satellite imagery from 1993 and 2000 (Barras et al., 2003).

Coastal lands loss is a high visibility problem along the Gulf Coast, especially in the Mississippi Delta.

- USGS and NGS state that the approximate rate of subsidence is between 1/3" to ½" per year; or about 4.2 ft/100 yrs
- Sea level rise is running about 1 ft/100 yrs (Burkett, Zilkowsi, and Hart, 2003)
- 15% of New Orleans is already more than -10 ft below sea level (URS, 2006)
- The average current rate of coastal land loss is between 25 and 118 square miles per year (the record of 118 mi^2 being a result of Hurricanes Katrina and Rita in 2005)
- The 2050 Reclamation Plan would restore 25 to 30 mi^2 over the next 40 to 50 yrs at a cost of $14 billion

The USGS National Wetlands Research Center has determined that Hurricane Katrina created as much new standing water area in the Mississippi Delta (below sea level) as occurred naturally over the previous 50 years! This was due to increased traction shear, which tore out large tracts of peat bogs, to depths of several feet (USGS-NWRC, 2006).

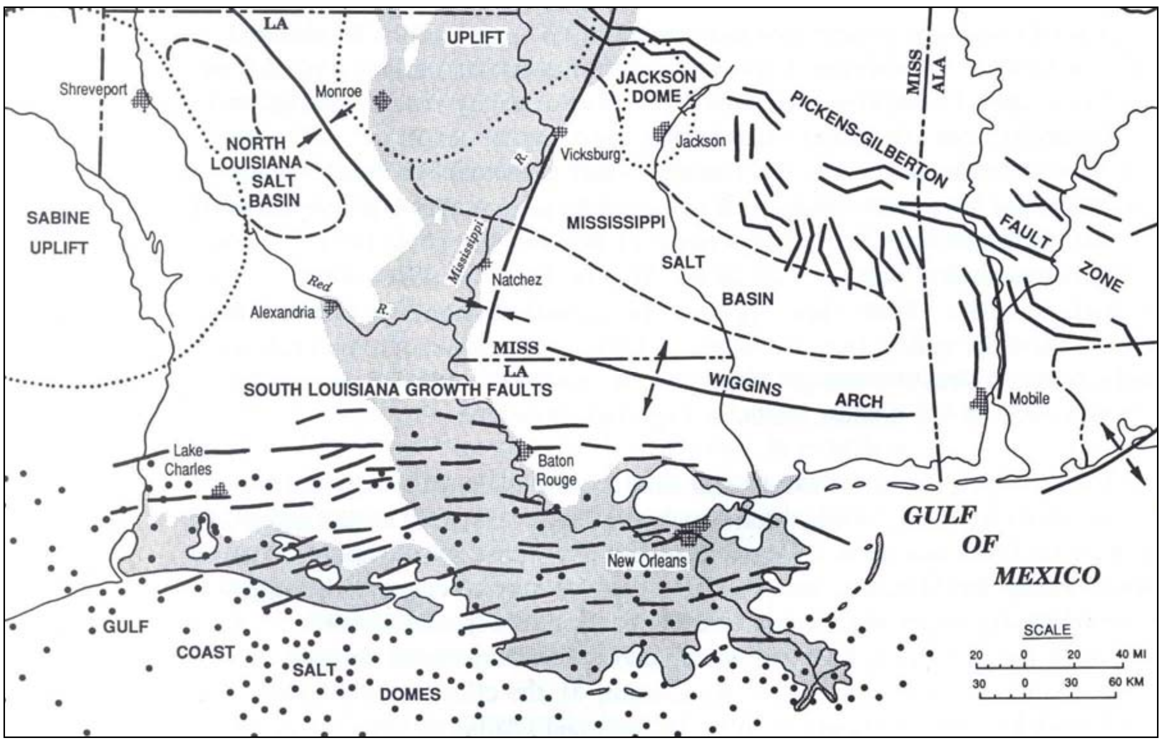

Figure 3.30: Structural geologic framework of the lower Mississippi River Delta, taken from Saucier (1994). Growth faults (solid black lines) perturb the coastal deltaic plain, as do salt domes (shown as dots). The nearest salt domes to New Orleans are 9 to 15 miles southwest of New Orleans. This study did not uncover evidence of growth faults materially affecting any of the levee failures from Hurricane Katrina, although such possibility exists.

3.7.8 Negative impact of ground settlement on storm surge

As large tracts of land along coastal Louisiana sink below sea level, less protection is afforded inland areas from the destructive impacts of storm surges caused by hurricanes. The absolute level of storm surges on the Louisiana Coast is also likely exacerbated by the loss of coastal vegetation, such as cypress swamps, which mollify wave energy through mechanical obstruction and tortuous flow path (increased boundary shear) as high water sweeps onto the land. The diminution of storm surge height would depend on the speed and duration of the storm as it makes landfall, and the density and height of the cypress swamps and the vegetation they support.

Many figures have been cited in the non-technical literature in regards to this "protective impact;" the most common being that every 4-1/2 miles of mature cypress swamp absorbs one foot of storm surge coming from the Gulf (Hallowell, 2005). Although the concept of storm surge mollification through turbulent boundary shear at the ground surface is conceptually possible, we were unable to find any measurements that quantified this effect through credible scientific study of historic storm events (NRC, 2006).

3.7.9 Conclusions about ground settlement

Multiple physical factors have combined to cause marked historic settlement of the New Orleans area. These include:

1) The average silt load of the Mississippi River (550 million tons [mt] per year prior to 1950; now 220 mt/yr) causes continuous crustal loading of the Mississippi River Delta, causing isostasy-driven settlement, which has been recognized since 1937 (Meade and Parker, 1985; Russell, 1940, 1967).
2) Tectonic compaction caused by sediment compaction at great depths, with associated pressure ridges and fold belts.
3) Subsidence along the seaward side of lystric growth faults perturbing the Mississippi Delta.
4) Drainage of near-surface soils causing an increase in effective stress and resulting primary conmsolidation
5) Oxidation of near-surface peaty soils due to lowering of the groundwater table in developed areas, or drainage of historic marshes and swamp lands. This component is often exacerbated by New Orleans residents who routinely fill in portions of their yards adjacent to protruding foundations (Figure 3.28), driveways and sidewalks, creating additional loads on the compressible materials lying beneath them.
6) Consolidation of soft compressible soils (with high water contents), due to surcharging by earth filling and other man-made improvements.
7) Structural surcharging. Settlements measured in vicinity of downtown high rise structures suggests that a portion of the observed settlement may also emanate from deeper horizons, caused by loads transferred to those horizons along friction piles and caissons for heavy structures.
8) Fluid extraction of oil, gas, and water from the subsurface. Extraction of fluids and natural gas is a pressure depletion that increases effective stresses acting on underlying sediments, hastening consolidation.

9) Solutioning of salt diapirs (salt domes) and seaward migration of low density contrast materials (salt and mud), as well as large subaqueous slope movements on the continental slope and shelf. When large volumes of material move laterally, adjoining areas drop to compensate for the volumetric strain.

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