Geologic Conditions Underlying the 2005 17th Street Canal Levee Failure in New Orleans

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Abstract: A careful program of subsurface sampling and cone penetration test soundings was employed to characterize the geologic conditions beneath the failed portion of the 17th Street Canal levee in New Orleans, where a 150 m long section of the levee and floodwall translated up to ~16 m when flood waters rose to 1–2 m of the wall's crest on August 29, 2005, during Hurricane Katrina. The subsurface conditions are characterized by discrete layers of fill placed upon the historic cypress swamp, which is underlain by a deeper, prehistoric cypress swamp. These swamp deposits were consolidated beneath the levee, and in the area of the 2005 failure, the swamp materials infilled a natural depression believed to be an old slough, which dipped below the sheetpile tips for a distance of about 50 m, which corresponds to where the breach appears to have initiated. Detailed examination of the recovered soils suggest that recent hurricanes periodically inundated the swamps with saline and/or brackish water, which cause a mass dieoff of swamp vegetation and flocculation of suspended clays, due to the sudden increase in salinity. These conditions promote deposition of discontinuous clay seams beneath layers of organics, which are then covered by fresh water swamp deposits. This sequence is repeated, like a series of tree rings, throughout the swamp deposits. The cypress swamp deposits lying beneath the levee also exhibit high hydraulic conductivity. These materials contain corky wood, and recovered samples often exhibited densities less than water. Nine of the post-Katrina borings recovered intact samples of a basal rupture surface comprised of organic silty clay exhibited near zero residual shear strength after shearing 80 to 100 mm.

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Introduction

Hurricane Katrina brought devastation to New Orleans and the surrounding Gulf Coast Region on August 28–29, 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 the Inner Harbor Navigation Canal (commonly referred to as the "Industrial Canal" in New Orleans) failed, either by overtopping or underseepage. 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 17th Street drainage canal wall was not overtopped. It appears to have suffered a massive foundation failure when water rose to within 1.5–1 m beneath the crest of the flood wall built on the crest of the old levee in 1993. This led investigators to examine the foundation conditions carefully beneath the breached levee section along the eastern side of the 17th St. Canal, a few blocks from its mouth along Lake Pontchartrain.

The writers participated in posthurricane field reconnaissance in the fall of 2005 and subsurface investigations carried out between January and April 2006 in and around the devastated areas surrounding New Orleans. During these trips the writers collected physical data on the levee failures, much of which was subsequently destroyed or covered by emergency repair operations on the levees. The writers also logged subsurface exploratory borings to characterize the geological conditions present in and around the principal levee failure sites, including that along the 17th St. drainage canal.

Evolution of Mississippi Delta beneath New Orleans

The Mississippi River drains approximately 41% of the Continental United States, a land area of 3.2 million km^2. The great majority of its bed load is deposited as subaerial sediment on a well

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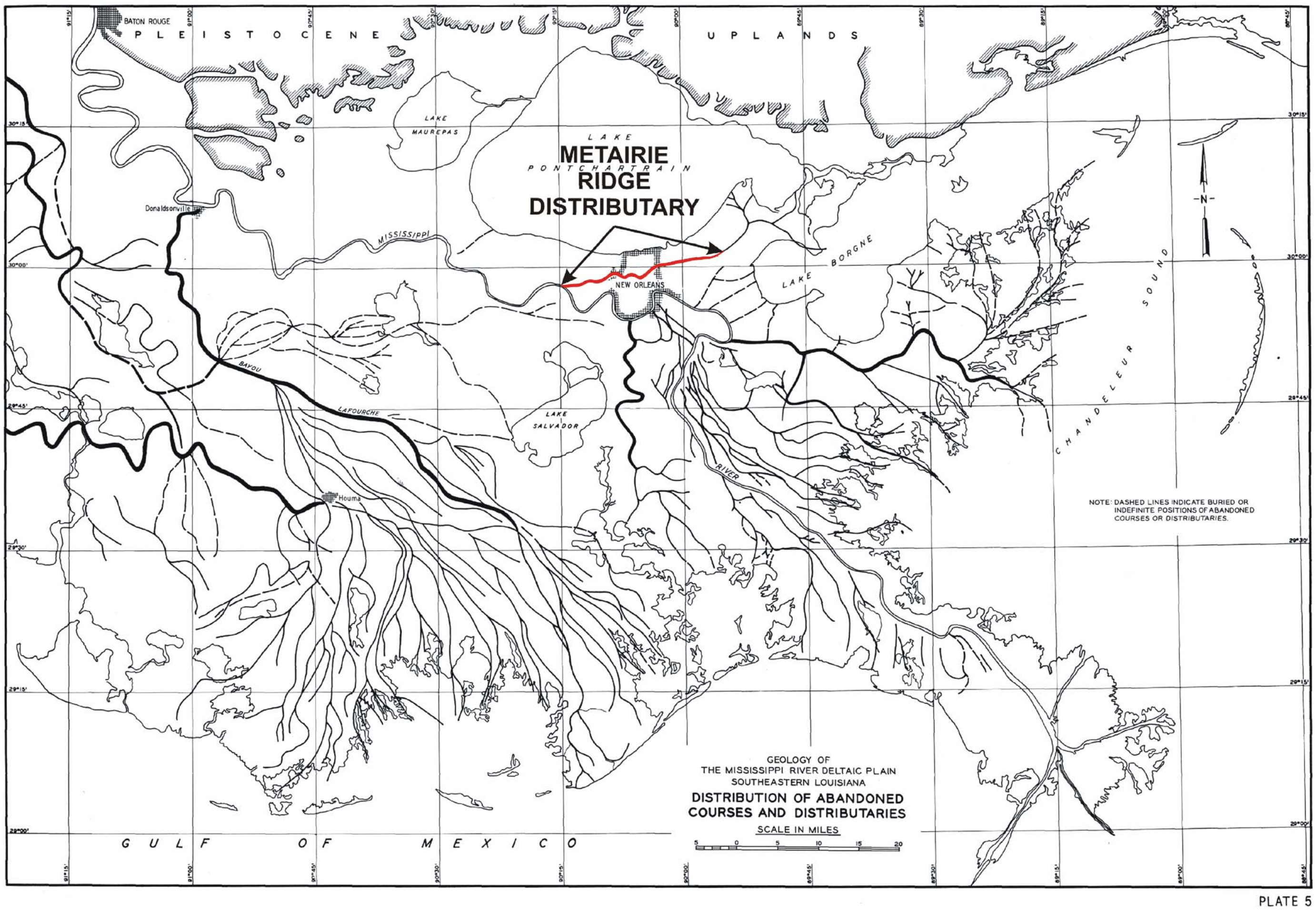

Fig. 1. Areal distribution of abandoned channels and distributaries of Mississippi River (from Kolb 1958). Metairie Ridge distributary channel (labeled) lies between two different depositional provinces, bifurcating New Orleans into two distinctly different geologic provinces.

developed flood plain upstream of Baton Rouge, as opposed to subaqueous deposits in the Gulf of Mexico. The Mississippi Delta has been laid down by an intricate system of distributary channels that periodically overflow into shallow swamps and marshes lying between the channels (Fig. 1). 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).

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 107 m, causing the Gulf of Mexico to advance into southeastern Louisiana inundating vast tracts of coastline. By 7,000 years ago sea level had risen to within about 9.15 m of its present level. By 6,000 years ago the Gulf had risen to within 3–4.5 m of its present level.

The modern Mississippi Delta is a system of distributary channels that have deposited large quantities of sediment over the past 6,000–7,000 years (Fig. 1), as sea level was rising. Six major depositional lobes, or coalescing zones of deposition, have been recognized in southeastern Louisiana (Saucier 1994). Four of these lobes 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 80+km of the modern Plaquemines-Balize Delta downstream of New Orleans has all been deposited in just the last 800–1,000 years (Draut et al. 2005).

During this same period (last 7,000 years) the Mississippi River has advanced its mouth approximately 518 river km into the Gulf of Mexico. The emplacement of jetties at the river's mouth in the late 1870s served to accelerate the seaward extension of the main distributary passes (utilized as shipping channels) to an average advance of about 70 m/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 increasingly 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. During the Quaternary period, or Ice Ages, (11,000–1.6 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 1,100 m. These stiff undifferentiated Pleistocene sands

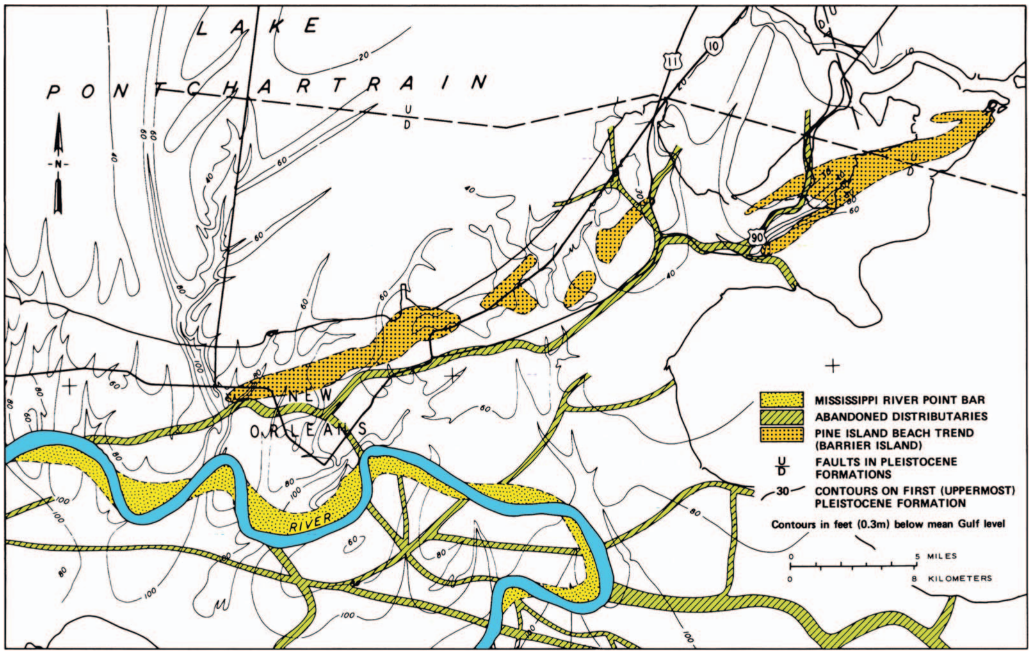

Fig. 2. (Color) Pleistocene geologic map of New Orleans area (adapted from Kolb and Saucier 1982). Stippled bands are principal distributary channels of lower Mississippi during early Holocene, while present channel is shown in light blue. Pine Island Beach Trend is shown in dotted pattern. Depth (in feet) on upper Pleistocene age horizons are shown as subdued contours.

and gravels generally lie 12–46 m 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).

Just south of the Louisiana coast, the Mississippi River sediments reach thicknesses of 9,150 m, or more. Through isostasy, the enormous weight of this sediment mass has caused the earth's crust to sag, creating a structure known as the Gulf Geosyncline (Saucier 1994). Flow of mantle material from below the Gulf Geosyncline is causing an uplift along about the latitude of Wiggins, Miss. This is only one of about nine mechanisms causing historic subsidence in Southern Louisiana (Chap. 3 in Seed et al. 2006).

Fig. 2 presents a generalized geologic map of the New Orleans area, highlighting the salient depositional features that define the various geomorphic provinces lying beneath the developed areas. Depth contours on the upper Pleistocene age (late Wisconsin glacial stage) land surface are shown as subdued contours. Sea level was about 30 m (100 ft) lower than present about 9,000 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. This early Holocene drainage system emanated from the Lake Pontchartrain depression and reached depths of 46 m below present 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 these are the materials that have undergone significant settlement, especially where variations in thickness are severe, such as the Garden District.

Pine Island Beach Trend

Relict beach deposits emanating from the Pearl River are shown in stippled yellow in Fig. 2. 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 4,500 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 indicates 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 had 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 1,645 km^2).

Sometime after this spit formed, distributaries of the Mississippi River (shown as stippled bands in Fig. 2) 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 7.6–13.7 m over the past 5,000 years (assuming it once stood 1.5–3 m above present sea level). The distribution of the Pine Island Beach Trend across lower New Orleans is shown in Fig. 3. The Pine Island sands reach thicknesses of more than 12 m 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

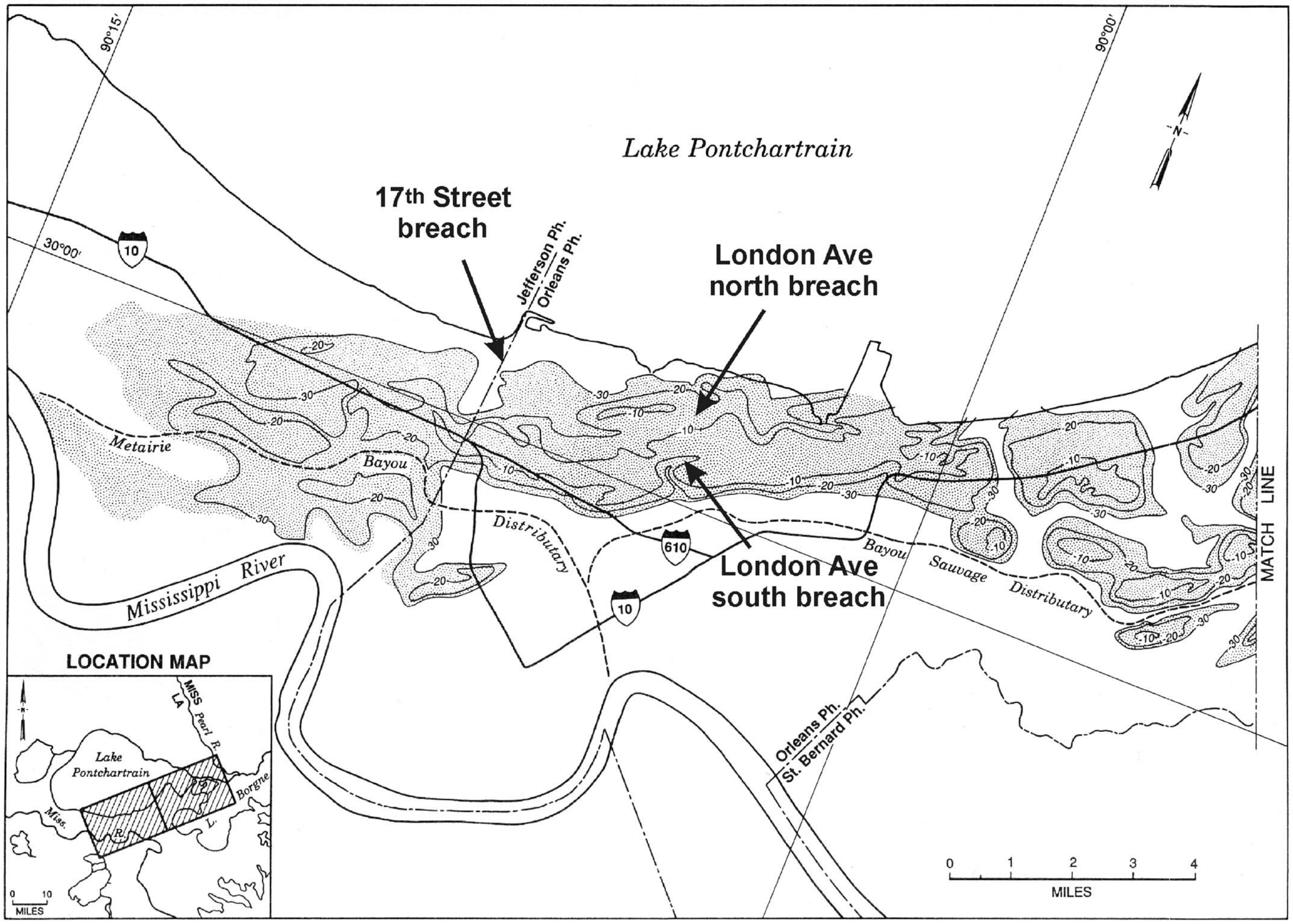

Fig. 3. Areal distribution and depth to top of formation isopleths for Pine Island Beach Trend beneath lower New Orleans, (adapted from Saucier 1994). This unit controlled underseepeage related breaks along London Avenue Canal, but was not significant factor in 17th St. Canal breach, 8.5 km west.

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 et al. 1975). The Pine Island Beach Trend peters out beneath Jefferson Parish, as shown in Figs. 3 and 7.

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 Fig. 4. 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 and 1878 on interdistributary embayments, which are underlain by fat clays deposited in a quiet water, or paludal, environment (Kolb and Van Lopik 1958).

Interdistributary sediments are deposited in low lying areas between modern distributary channels and old deltas of the Mississippi River, shown schematically in Fig. 5. The low angle bifurcation of distributary streams promotes trough-like deposits that widen towards the gulf. 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 distributaries. 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.

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 somewhere between 100 and 488 and 1953 Pa (100 to 400 lbs/sq. ft). These strengths, of course, also depend on previous periods of desiccation and effective overburden pressures.

Careful logging is required to identify the depositional bound-

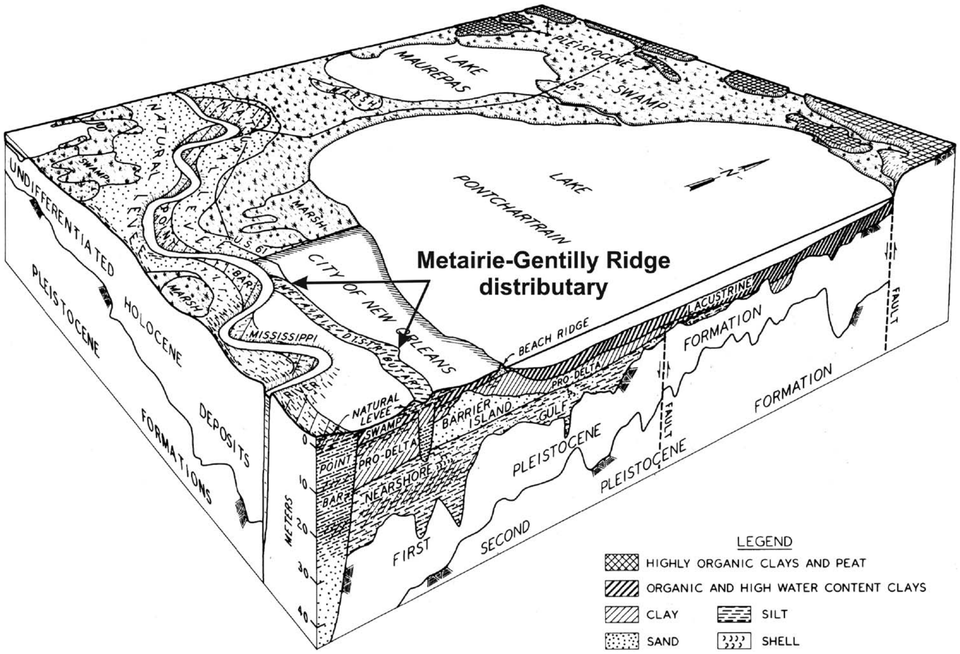

Fig. 4. Block diagram of geology underlying New Orleans (adapted from Kolb and Saucier 1982). Principal feature dividing New Orleans is Metairie distributary channel, shown here, which extends to depth of 15 m below MGL and separates geologic regimes on either side. Note underlying faults, especially that bounding northern shore of Lake Pontchartrain.

ary between interdistributary (marsh and swamp) and prodelta clays. 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 (75 km downstream of New Orleans) exhibit little increase in strengths to depths of as much as 114 m (375 ft). This is because these materials were deposited rapidly, during the past 600–1,000 years, and insufficient time has passed to allow them to consolidate, given the low drainage characteristics of the units. 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 bulk density, water content, and soil strength.

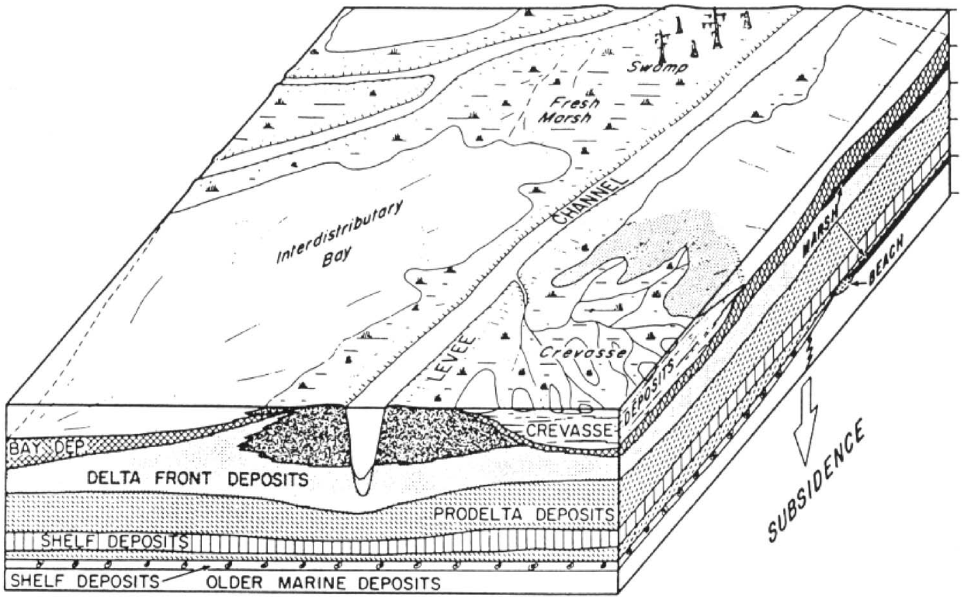

Fig. 5. Block diagram illustrating relationships between subaerial and subaqueous deltaic environments in relation to single distributary lobe (taken from Coleman and Roberts 1991). Lakeview and Gentilly neighborhoods of New Orleans are underlain by interdistributary sediments, overlain by peaty soils laid down by fresh marshes and cypress swamps.

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 by halfland and halfwater, with water depths seldom exceeding 0.61 m (2 ft) above mean gulf level. Ninty percent 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.

Marshes

More than half of the New Orleans area was once 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.

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 downward, 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, which are noted in many of the older maps, such as that prepared in 1849 (WPA-LA 1937).

Peats are the most common type of organic 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 fluvitile 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 water courses, 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 are repeatedly subjected to fresh water inundation. In most instances an upper mat of roots and plant parts at least 0.3 m 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 0.1 and 0.36 m thick, floating on 1–4.5 m 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 0.1 and 0.2 m thick and underlain by 0.30–3 m 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 0.5 to 0.2 m 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 0.8–13 km wide flanking the present day shoreline, along the coast.

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 13.8–20.7 kPa 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 1.8 m, which exert pressures close to those cited above.

Cypress Swamps

Before development, swamps in the New Orleans were easily distinguishable from marshes because of the dense growth of cypress and gum trees. All of the pre-1900 maps make reference to extensive cypress swamps in lower New Orleans, between the French Quarter and Lake Pontchartrain. Encountering cypress wood in boreholes or excavations is generally indicative of a swamp environment. These cypress swamps thrived in 0.6–1.8 m of water, but cannot regenerate unless new influx of sediment is deposited in the swamp, reducing the water depth to something less than 0.6 m (seedling cypress trees cannot survive in deeper water). Brackish water intrusion can also cause flocculation of clay and premature dieout of the cypress trees.

Two prehistoric cypress swamps have long been recognized to extend over large tracts of New Orleans (WPA-LA 1937). The historic swamp occupies the predevelopment 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 4.6–9 m below the original ground surface (around −7.6 m mean gulf level, which can be converted to NAVD88-2004.65 for the present elevation). This older cypress-gum swamp

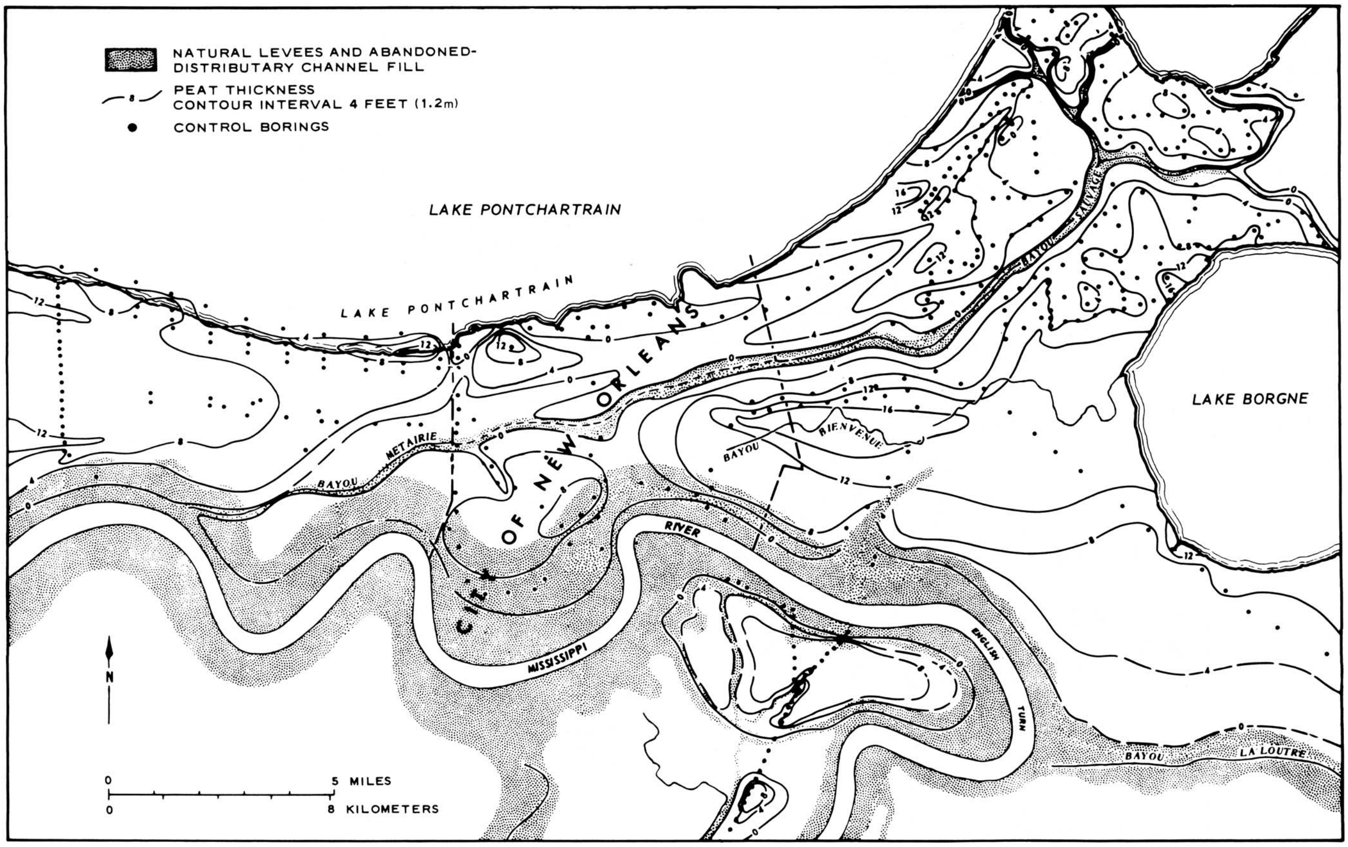

Fig. 6. Distribution and apparent thickness of recent (surficial) peat deposits in vicinity of New Orleans, taken from Gould and Morgan (1962)

forest was undoubtedly killed off and buried in a significant prehistoric 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, which was a common occurrence during the most damaging floods that affected the city prior to 1849.

The two principal types of swamps in the New Orleans area are 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 dieoff is readily seen in the form of countless dead tree trunks, which become buried in the marsh (without trees) that eventually 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 6–7.6 m in Plaquemines Parish. A typical soil column in a mangrove swamp consists of a thin layer of soft black organic silty clay with an interlocking root zone that averages 0.13 and 0.3 m thick. Tube-like roots usually extend a few inches above the ground surface. Thicknesses of 1.52 m (5 ft) 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 manmade 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). The surficial peats are typically comprised of organic materials derived from swamps, marshes, and paludal interdistributary embayments. They reach a maximum thickness of ~5 m, as shown in Fig. 6. Most of the foundation distress for light residential structures in New Orleans is attributable to differential settlement engendered by recent dewatering of these peaty deposits.

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 meters in diameter to the largest, Lake

Salvador (southwest of New Orleans), which measures 10 by 21 km. Lake Pontchartrain (40×64 km) is much larger, but is not a true marshland lake. The depths of these lakes varies, from as little as 0.5 m to about 2.5 m (Lake Pontchartrain and Lake Borgne average 4.6 and 3 m 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 0.3–0.6 m deep, even though they are up to 1.6 km 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 a lake. The ooze become increasingly cohesive with age and depth, but are generally restricted to only 0.3–1 m in thickness in the small inland lakes.

Transitional lakes are those that become larger and more numerous closer to the actively retreating shoreline of the delta. The 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 6–9 m 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, indicating 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 1970s.

During Hurricanes Katrina and Rita in 2005, wind shear removed extensive tracts of marsh cover, creating 306 km^2 of new water surface in the delta. 106 km^2 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 (USGS 2006).

Recognition Keys for Depositional Environments

Kolb and Van Lopik (1958) developed a protocol for classifying soils in New Orleans with their likely environments of deposition and physical traits. Marsh deposits are typified by fibrous peats; from three principal environments: (1) 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 marshes tend to be grass covered, developed on flat areas that are "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:

1. Cypress wood=fresh water swamp.
2. Fibrous peaty materials=marshes.
3. Fat clays with organics; usually lacustrine. A pure fat clay has high water content (w/c) and consistency of peanut butter.
4. Interdistributary clays; paludual environments; lakes—silt lenses when water is shallow and influenced by wind swept waves.
5. Lean clays CL liquid limit (LL) <50, silty and $w/c < 60\%$.
6. 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 76.2 mm (3 in.) Shelby tubes and 127 mm (5-in.) diameter piston sampler, referring to samples recovered from the 1.27 mm (5-in.) 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 (US Army Corps of Engineers 1990) by the modifier "U" for "undisturbed" samples (e.g., boring prefixes X-U, UMP-X, MUE-X, MUG-X, and MUW-X).

Holocene Geology of New Orleans

The surficial geology of the New Orleans area is shown in Fig. 7. The Mississippi River levees form the high ground, underlain by sands (shown as bright yellow in Fig. 7). The old cypress swamps and grassy marshlands occupied the low lying areas. The midtown area between the Mississippi and Metairie Ridge (shown in Fig. 2) lies within what is known as a "levee flank depression" (Russell 1967). The much older Pleistocene age prairie formation lies north of Lake Pontchartrain. This unit dips down beneath the city and is generally encountered at depths greater than 12 m in the city (described previously).

The levee backslope and former swamplands north of Metairie Ridge are underlain by four principal stratigraphic units, shown in Fig. 8. The surface is covered by a thin veneer of recent fill, generally 0.10–1 m 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. This unit contains two levels of old cypress swamps, discussed previously, and varies between 3 and 12 m 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 4.5 m beneath the 17th Street Canal, 4.8 km 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.

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 9 m. It thins westward towards Jefferson Parish, where it is only about 3 m thick beneath the 17th Street Canal, as shown in Fig. 8. The Pine Island sands are easily identified by the presence of mica in the quartz sand,

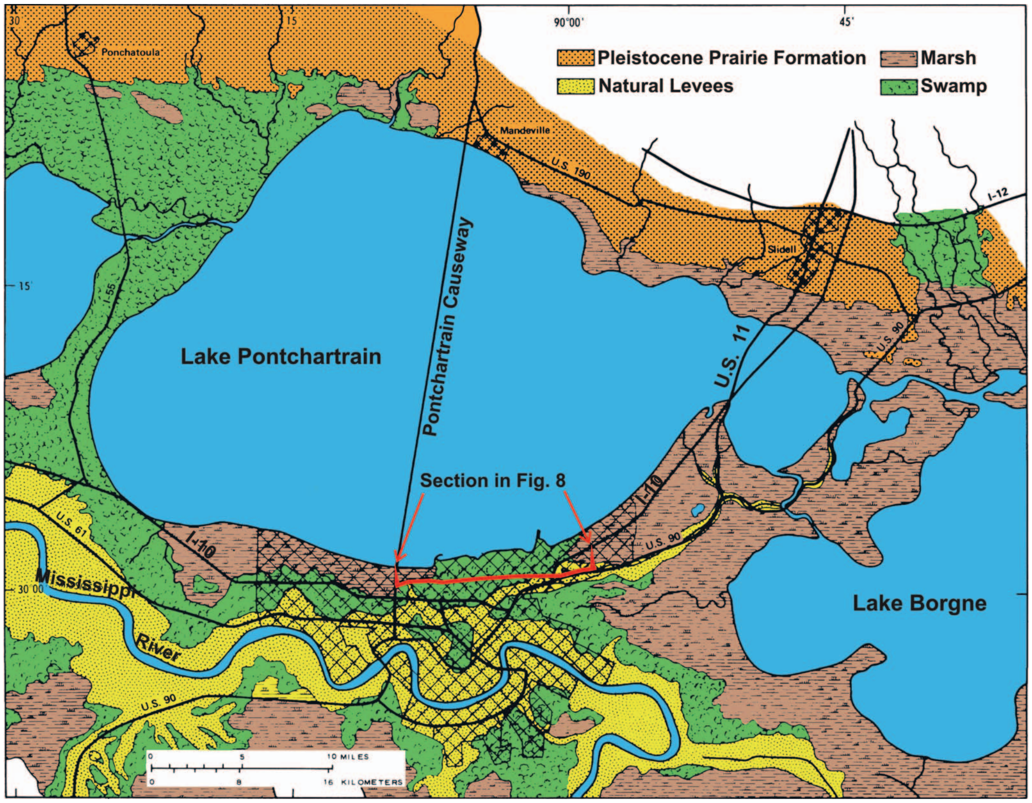

Fig. 7. (Color) Geologic map of greater New Orleans area (adapted from Kolb and Saucier 1982). Sandy materials shown in yellow are natural levees, green areas denote old cypress swamps, and brown areas are historic marshlands. Stippled zone indicates urbanized portions of New Orleans. Geologic section shown in Fig. 8 runs parallel to south shore of Lake Pontchartrain, as indicated by red section line.

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 extends westward from the approximate position of the Inner Harbor Navigation Canal, where it lies at a depth of ~12 m. In this area it is about 3 m thick, but thickens westward, increasing to ~10.7 m just east of the 17th Street Canal (Fig. 8).

The Holocene deposits reach their greatest thickness just east of the 17th Street Canal where they extend to a depth of 24 m

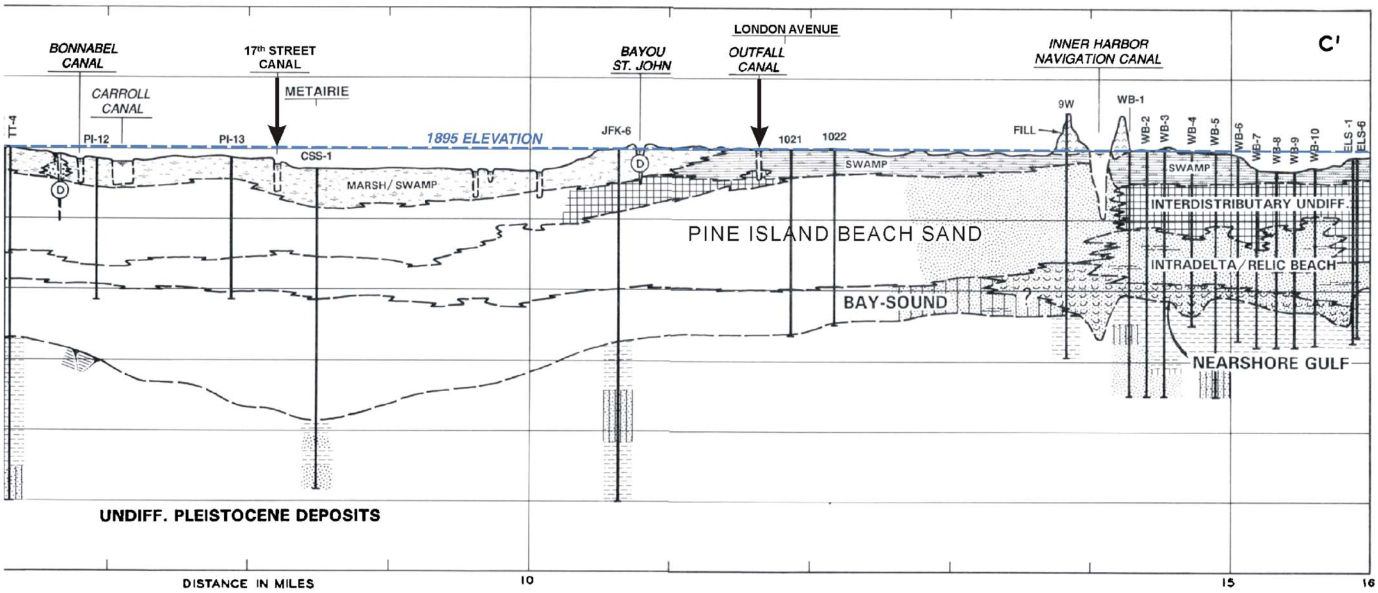

Fig. 8. Geologic cross section along south shore of Lake Pontchartrain in Lakeview, Gentilly, and Ninth Ward neighborhoods, where the 17th Street, London Avenue, and IHNC levees failed during Hurricane Katrina. Notice apparent settlement that has occurred since city survey of 1895 (upper dashed line), and correlation between settlement and marsh-swamp deposits. This east-west section was (adapted from Dunbar et al. 1994).

thick (Figs. 2, 3, and 8). Undifferentiated Pleistocene deposits lie below these younger deposits. It is interesting to note that this area has experienced the greatest recorded settlement in the city, attributable to dewatering of the marsh/swamp units above compressible lacustrine clay. The areas to the east are underlain by much more sand which, being less compressible, has experienced less historic settlement (see 1895 elevation on Fig. 8).

The Lakeview-Gentilly neighborhoods bordering Lake Pontchartrain (profiled in Fig. 8) lie 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 (Fig. 1). The same is true for the French Quarter and downtown New Orleans which are built on the natural sand levee of the Mississippi River, which occupy the highest ground in the city.

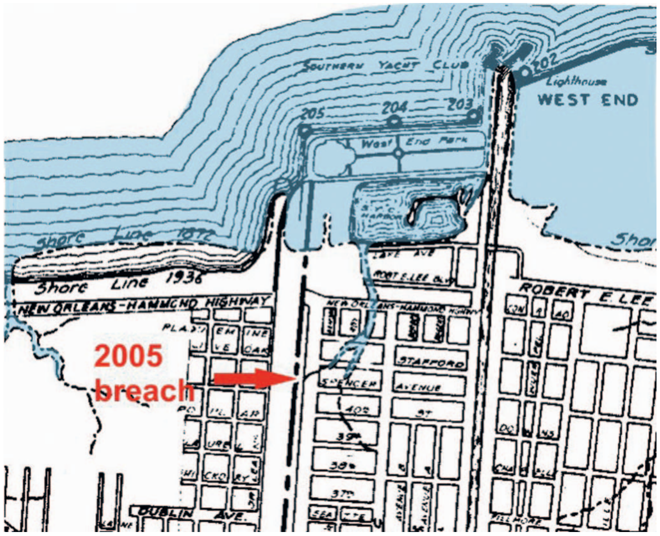

Fig. 9. (Color) Overlay of 1872 map by city engineer Valery Sulakowski on 1937 assessors parcel map, as presented in WPA (1937). This map compares 1872 shoreline with that in 1936 and shows historic sloughs that drained cypress swamps along Lake Pontchartrain prior to development in later half of 20th century. Although land was subdivided, only few structures had been constructed in this area prior to mid 1950s. Position of 2005 breach along east side of 17th Street Canal is indicated by arrow.

Geologic Conditions at 17th Street Canal Breach

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 up to 15.5 m (51 ft) riding on a weak layer of organic-rich marsh and swamp deposits, which included seams of grey paludal clays, between 10 and 300 mm thick. 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.

During the geotechnical exploration for the concrete flood walls in 1980–1981, three of four borings in the vicinity of the 2005 breach failed to recover subsurface samples. These borings were spaced 152 m (500 ft) apart. We have been informed that because of strict budgetary constraints, a fateful decision was made to linearly extrapolate the respective stratigraphic contacts between the next adjacent borings that recovered samples, which were located 610 m (2,000 ft) apart. The sheetpile tip elevations were then based on the assumed depth of the contact between the relatively pervious swamp materials and the underlying lacustrine clay, and recommending the sheetpiles extended 0.6–1 m past this imaginary horizon. This assumption appears to have been well founded, except where the failure occurred, because the swamp/clay contact dipped downward, across a natural depression about 100 m wide.

Interpretation of Geology from Auger Borings and Cone Penetration Test Soundings

A series of continuously sampled borings was conducted and logged using 76.2 mm (3.0 in.) Shelby tubes in the vicinity of the 17th St. Outlet Canal levee failure to characterize the geology of the foundations for the levee embankments and floodwalls. Drilling on the east (Lakeview) bank was carried out on an intact portion of the translated levee embankment while drilling on the west (East Jefferson Parish) side took place directly across the canal from the middle of the eastern breach. This drilling uncovered a wide range of materials and provided insights into the failure.

Drilling on the east side of the levee commenced at an elevation approximately 0.6–0.9 m above sea level. A thin layer of crushed rock fill placed by the Corps of Engineers to provide a working surface at the breach site had to be penetrated before reaching native materials. On 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 along the southern shore of Lake Pontchartrain (Fig. 9), Fig. 9 also shows how the southern shoreline of Lake Pontchartrain had eroded southward prior to stabilization by protective levees, after the 1947 hurricane flooded this area. In the depth interval 1.2–1.8 m, highly permeable marsh deposits were encountered and drilling fluid began flowing from a cone penetration test (CPT) hole several feet away, indicative of almost instantaneous conductivity at this depth. The bottom of this sampling round recovered as a solid 76.3 mm core of orange-red cypress wood indicating that this boring had passed through a trunk or stump of a former tree, subsequently dated as 1,350 years before present (YBP) using Carbon 14 (C_{14}) methods (described later). The marsh deposits consist of soft clays and organic clays usually associated with organic material (wood and roots). The organic materials are readily identifiable by observing noticeable jumps in the friction ratios of the CPT logs. The thickness of swamp/marsh deposits was found to be ~2.9 m on the west bank of the canal and between 1.2 and 1.8 m on the east bank of the canal. The depth at which swamp/marsh deposits were encountered on either side of the canal varied from approximately −2.6 m on the west side to −3.0 m on the east side (using the NAVDD882004.65 datum).

An intermixing zone was identified between the swamp and lacustrine deposits. This stratum consists of a mixture of soft clays, silt lenses with little or no organic material. The thickness of intermixing zone ranges from 0.9 to 2.6 m on the east bank of the canal. A sensitive layer of organic silty clay about 25 mm thick was consistently noted between the swamp/marsh deposits and this intermixing zone, which appears to have accommodated much of the translational movement when the levee failed. This layer appears to be the slide plane which accommodated the translational failure of the 17th Street canal embankment. It was encountered in all of the borings adjacent to the displaced levee, at depths between 2.53 and 3.35 m below the postfailure working surface, so depended on location. This weak horizon was generally observed to be between 19 and 25 mm thick and exhibited variations in depth and inclination, as shown in Fig. 12. Gray plastic clays of lacustrine origin appear to have been mixed with dark organics by shearing, and this zone was extremely mushy and almost soupy in texture, difficult to sample, and suggestive of sensitivity to strain. This seam exhibited a peak shear strength of 1.9–2.5 kPa, decreasing to a near zero residual strength after 40 to 120 mm of displacement (Seed et al. 2007). The in situ water content of this horizon was as high as ~280% in some of the recovered samples, likely ascribable to dilation during shearing. No intermixing zone was discerned beneath the west bank of the canal (Fig. 15). The contact between swamp/marsh and intermixing zone suggests that the organic materials were mashed down, on an eroded surface in the underlying lacustrine deposits, typical of a slough channel (Fig. 9).

Organic rich deposits continued to a depth of about 6 m 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 in shallow bodies of water. The clays are usually gray in color, but other colors, such as olive, brown, dark gray, and black were also observed, depending on the organic content. Some organic matter towards the base of this deposit appeared to be 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 commercially marketed 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 a depth of 5.2 m on the west side to between 4.3 and 7.0 m on the east side 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 8 m. It is likely that the silt and organics were washed into an otherwise quiet prehistoric Lake Pontchartrain by storms. No organic matter was found in these deposits. The thickness of lacustrine deposits at this site were 5.2–5.8 m on the west bank of the canal and 4.6–6.7 m on the east bank (Fig. 15). The difference on the east side is likely ascribable to the small slough channel that terminates in this area, noted in Fig. 9.

Sand and broken shells were encountered 9 m below ground surface and continued to increase in quantity and size to a depth of 10.8 m, when the material became dirty sand, with very little cohesion. This beach sand is identified by its sand and silty sand content. It is easily recognized in the CPT soundings by a large jump in tip resistance and corresponding drop in the pore pressure (see Fig. 15). The depth at which beach sand encountered ranges from −11.3 m on the west side to −11.0 m on the east side, with a fairly uniform thickness of 1.83 m. These sands contain mica, and appear to be the Pine Island Beach Trend described by Saucier (1963), discussed previously. Regional data suggest this unit thins markedly to the west (Saucier 1963, 1994).

The lowest stratigraphic unit penetrated in the post-Katrina borings and soundings were the Bay Sound deposits. This unit contains stiff organic clays and stiff clays. It is easily recognized in the CPT soundings by a large drop in the tip resistance with a corresponding increase in pore pressure (Fig. 15). Bay Sound deposits were only encountered on the east side of the canal because the soundings on the west side were not taken to sufficient depth. This unit was encountered at depths between −12.5 and −13.3 m.

The geologic conditions beneath the 17 Street Canal breach are shown in Figs. 10–15. Fig. 11 shows the relative positions of the borings and cross sections presented in Figs. 11–13. The series of cross sections shown in Fig. 12 are intended to illustrate the failure sequence at the point of maximum translation along the 17th Street Canal breach. Postfailure profiles were constructed using Brunton compass and tape techniques described in Compton (1962). In this section the land side of the eastern levee embankment translated laterally, up to 15.5 m, with negligible vertical differential. The embankment fill reaches a thickness of ~3 m on the west bank of the 17th Street Canal (shown in Fig. 15). Just north of the breached area (east bank), the thickness of the fill ranges from 4.3 to 4.9 m. Artificial fill materials for the canal embankments appear to have been placed in three sequences: (1) during the original excavation of the canal, around 1858; (2) again, after the 1915 Grand Isle Hurricane (separated by a thin layer of bivalve shells, likely used to pave the old levee crest prior to 1915); and (3) once more, after the October 1947


(a)


(b)

Fig. 10. Upper image provides overview of 17th St. canal breach, looking east. Breach is about 150 m long. Lower image shows oblique view of translated embankment, with intact concrete flood wall at lower left. Land side of levee translated up to 15.85 m, with little vertical differential. One section of concrete I-wall tilted forward (left foreground) while most of wall appears to have been carried entire distance before falling backward, towards canal (upper center). Images from Federal Emergency Management Agency.

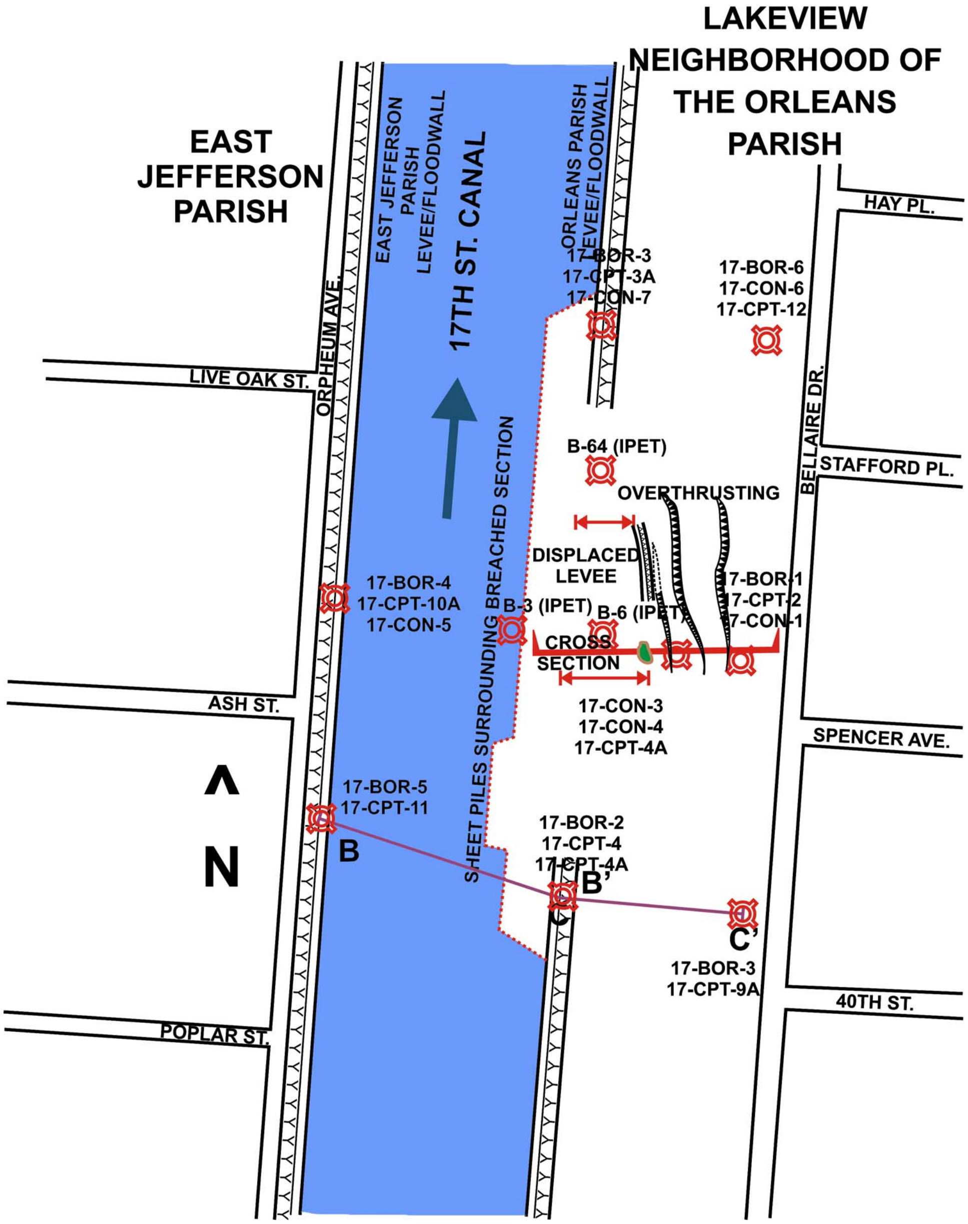

Fig. 11. Site plan of 17th Street Canal breach site after failure of August 29, 2005. Solid line with bounding bars (at middle right) indicate position of geologic sections in Fig. 12, while Section *B-B′-C* is shown in Fig. 15.

hurricane, and prior to intense residential development adjacent to the canal, which occurred between 1950 and 1975.

A distinctive basal rupture surface was encountered in all the exploratory borings at the 17th St. Canal failure site, as depicted in Section No. 6 of Fig. 12. The basal rupture surfaces were characterized by abrupt truncation of organic materials, including cypress branches up to 50 mm in diameter. The rupture surface was between 19 and 25 mm thick, and generally exhibited a very high water content (between 135 and 279% in samples recovered and tested). This material had a liquid consistency with no appreciable shear strength. It could only be sampled within more competent materials in either end of the Shelby tubes. A disturbed mixing zone 70 to 100 mm thick was often observed in the horizon immediately above the basal rupture surface. This mixing zone contained angular chunks of clay with contrasting color to the matrix materials, up to 80 mm across, along with severed organic materials, including cypress branches up to 50 mm in diameter.

A series of balanced cross sections were constructed using the principles described in Woodward et al. (1989), based on field measurements of the breach area where the translated block was best preserved (Section No. 6 in Fig. 12). Lateral offsets were based on tape measurements made from the chain link right of way fence along the displaced levee crest. In this area four distinct thrust surfaces were identified in the field, suggesting a planar, translational failure mode, as sketched in Sections 2–6. The old swamp contained discontinuous stringers of sensitive clay, several which exhibit evidence of overconsolidation in the CPT soundings, typical of desiccated horizons (Seed et al. 2006, Chap. 8). The cross sections are intended to illustrate the kinematic

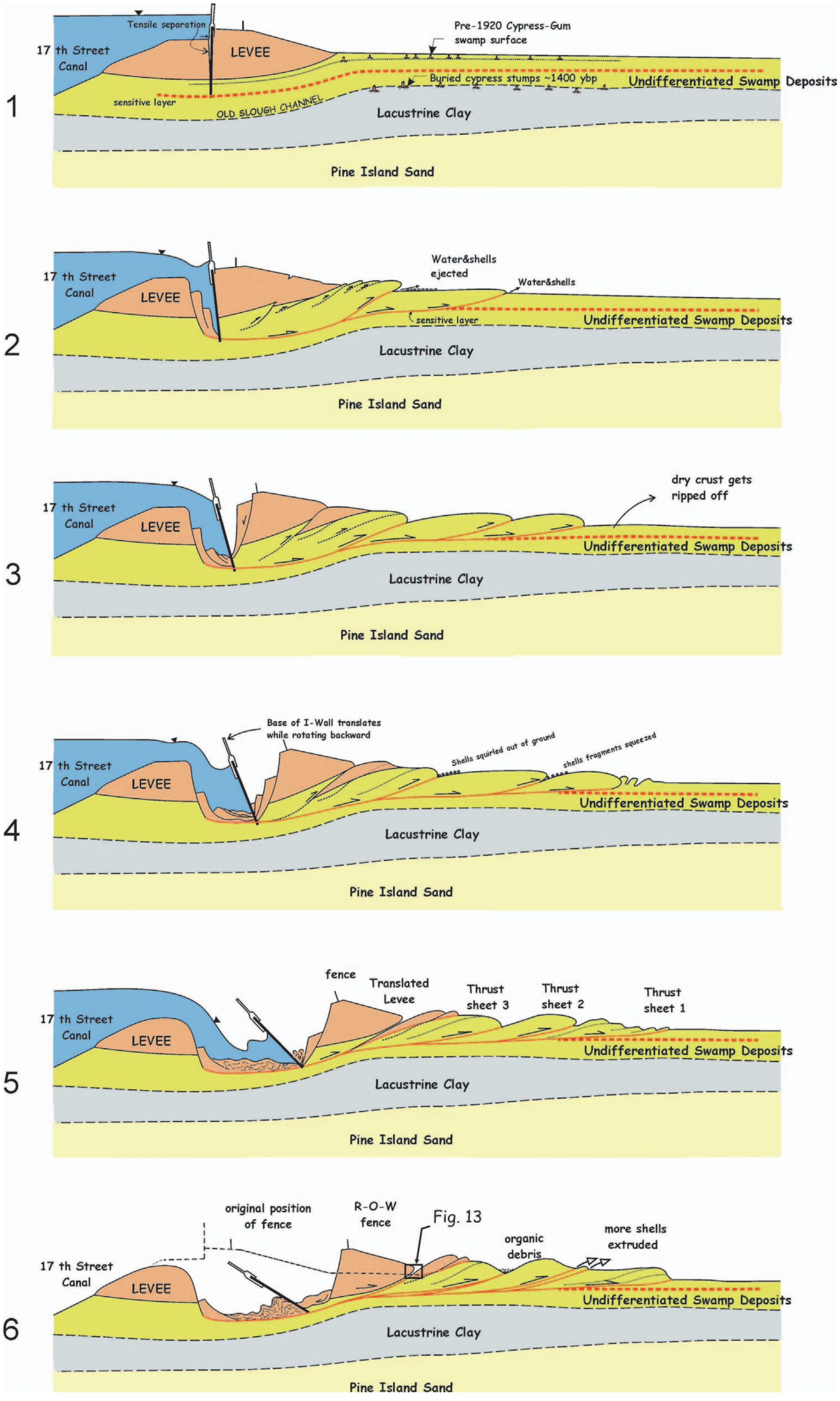

Fig. 12. (Color) Balanced structural cross sections through north side of 17th Street Canal breach, along transect shown in Fig. 11. Low residual strength of sensitive layer, high pore pressures along this same horizon, and desiccated soil cap combined to favor translational failure with multiple toe thrusts.

Fig. 13. (Color) Annotated photo of trench excavated into south end of displaced 17th St. canal levee (photo taken from IPET 2006). Thicker seam or gray lacustrine clay approximates position of thrust between base of levee embankment and Thrust sheet 3, noted as small box labeled Fig. 13 on Section No. 6 of Fig. 12. This lense dips about 25° west, back towards canal.

mechanisms involved in the progressive development of the thrust sheets, as the earthen materials translated on a sensitive low strength layer. This low strength horizon was encountered in all of the borings supervised by the writers, but required a careful sampling protocol, often requiring two or three attempts using piston samplers at each boring location. Thrust sheets commonly develop on low strength horizons subjected to high horizontal loads. The first thrust sheet was triggered by lateral pressure of the passive reaction block of the sheetpile bulkhead wall, which failed. After the first thrust sheet formed (which ended up being Thrust sheet 2, shown in Section No. 5 of Fig. 12), it translated over the adjacent ground and triggered another thrust sheet (Thrust sheet 1 in Section No. 5 of Fig. 12), which tore up the dry crust that typified the upper 1/2 m of the ground surface. The slip surfaces developed between the three thrust sheets all showed evidence of high pore pressures being developed during the translation, in the form of expelled freshwater bivalve shells, extruded from an underlying stratigraphic horizon. The toes of Thrust sheets 2 and 3 were both about 1.5 m high, and these extended through several of the damaged residential structures, lifting and offsetting their foundations (see areal pattern of the three thrust plates in Fig. 11). Thrust Sheet 3 was squeezed from beneath the levee embankment, late in the translation sequence. The entire failure likely took about less than 1 m to translate 15.5 m, the measured offset. About 55 m of the 17th St. Canal levee just south of this location was completely removed and destroyed by the outbreak flood that accompanied the breach, as was the northernmost section, about 30 m wide (Fig. 11).

The old swamp deposits are noticeably compressed beneath the eastern half of 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). Local differential settlement causes the contact between the swamp deposits and the underlying lacustrine clays to dip to the west, back towards the canal, and towards the tips of the sheetpile bulkhead wall supporting the concrete I-walls. This change in dip is complicated by a natural depression that cuts across this zone on an acute angle (about 45° to the canal alignment), indicated by "old slough channel" on Section No. 1, which may correlate with the old slough channel delineated by Sulakowski in 1872, reproduced in Fig. 9. This depression is laterally restricted to the zone between borings 17-CON-3/4 and 17-BOR-2, shown in Fig. 11. There was ample physical evidence of high pore pressures developing during failure and translation of the levee block, in the form of extruded bivalve shells and organic debris littering the ground surface at the toe thrusts (described in Seed et al. 2006, Chap. 3).

The Corps of Engineers' Interagency Performance Evaluation Team (IPET 2006) excavated a trench for sampling along the southern margins of the displaced levee block highlighted with green shading in Fig. 11. A photo of this excavation is reproduced in Fig. 13 and its approximate position noted by the box on Section No. 6 in Fig. 12. The senior writer revisited this same excavation a short time later, taking measurements and sketching the stratigraphic relationships exposed there. Several seams of grey lacustrine clay were observed sandwiched between blocks of peat and rolled fill from the levee embankment. Both of these clay seams were remarkably linear, insofar as they exhibited near-constant thickness. The largest seam was about 280 mm in diameter and dipped west-southwest (WSW) at 25° (see Fig. 13). The thinner clay bed was discontinuous, up to 100 mm thick, and dipping between 34 and 47° WSW. Slicken sides indicative of differential shearing were observed along the thickest seam, but the steep inclination of both horizons could not be resolved with a basal slip surface for a translational failure, with only 2 or 3° of back-rotation. After working with the spatial relationships, and surveyed positions of measured attitudes of the various slide planes exposed at the base of each Thrust block, a series of six cross sections were constructed (Fig. 12). These suggest that the 280 mm thick grey clay seam was likely associated with the initial series of en-echelon passive reaction wedges, created by the toe kickout of the still sheetpile bulkhead, most appreciated in Secs. 2, 3, and 4 of Fig. 12.

Planar translational failures are typical of situations where

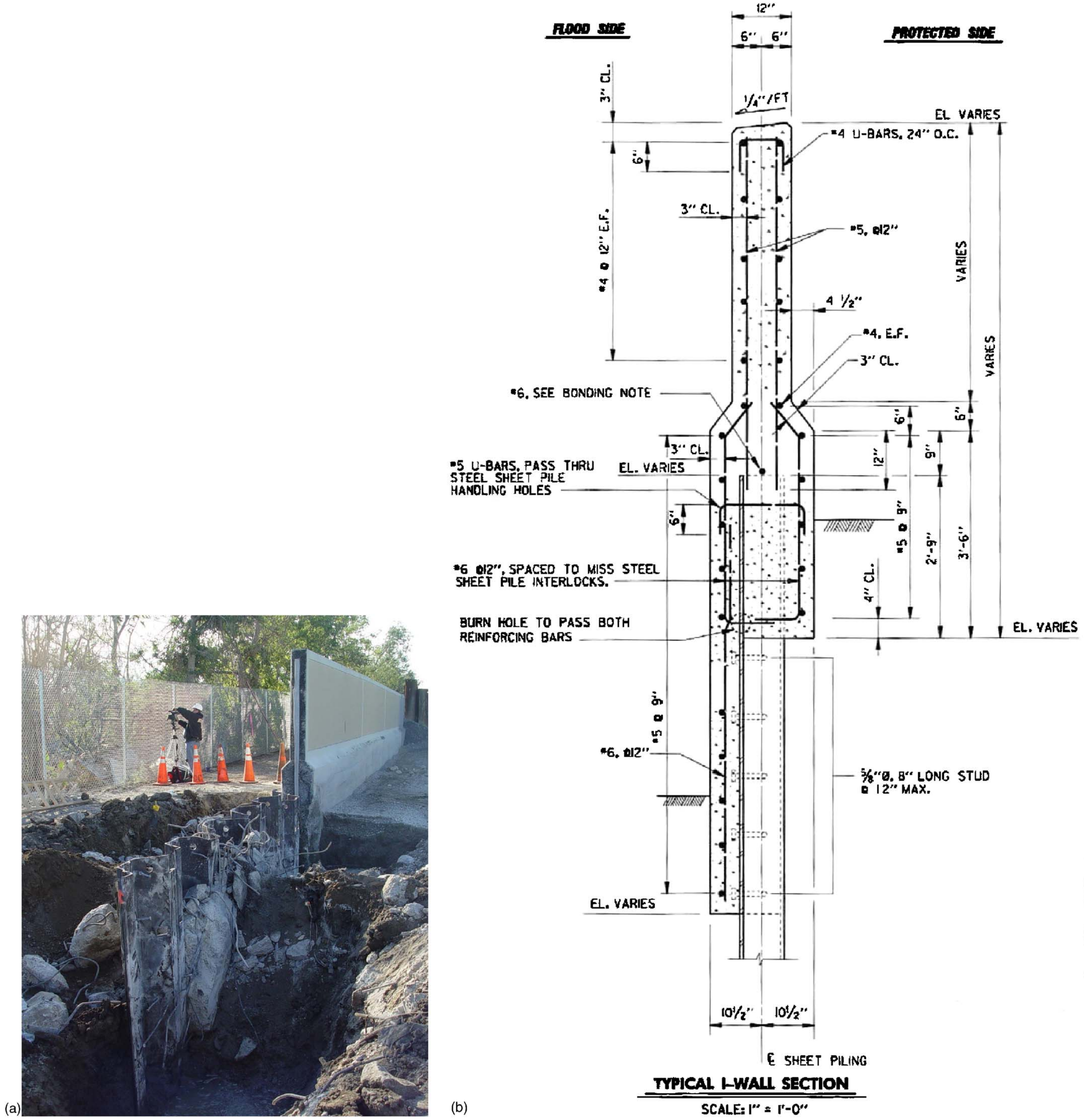

Fig. 14. Concrete I-wall constructed upon 17th Street Canal in 1993 on Hoesch 12 steel sheetpiles, 7.16 m long. Left view shows exposed sheets after concrete cap had been chipped off in preparation for pullout on December 13, 2005, as they appeared from canal side of wall. Right view shows design for concrete I-wall (viewed in opposing plane to that shown in photo) as constructed in vicinity of 17th St. Canal failure in 1993. Note asymmetry of thickened concrete cap, which extended 2 m on water side of embankment, but only 1 m on land side.

shear translation occurs along discrete and semi-continuous low strength horizons (Cruden and Varnes 1996). Additional evidence of translation is the relatively intact nature of the land side of the failed levee embankment, upon which the old chain link right-of-way 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 (Fig. 14). The writers observed the displaced concrete I-wall solidly attached to the Hoesch 12 steel sheetpiles, without appreciable distortion (Fig. 10). Each sheet segment was about 0.58 m (as measured along the wall alignment) and 0.28 m deep, with an open Z pattern (Fig. 14). The plate thickness of the sheets was about 11 mm (7/16 in.). Postfailure examination revealed that the sheetpiles were 7.16 m long and were embedded approximately 0.6–0.9 m into the footings of concrete I-walls (Fig. 14). The sheetpiles and attached I-walls formed a stiff rigid element. Along the middle of the breach area the flood wall fell backward (towards the canal) *after* translating approximately the same distance as the land side of the levee embankment (see Sec. 6 in Fig.

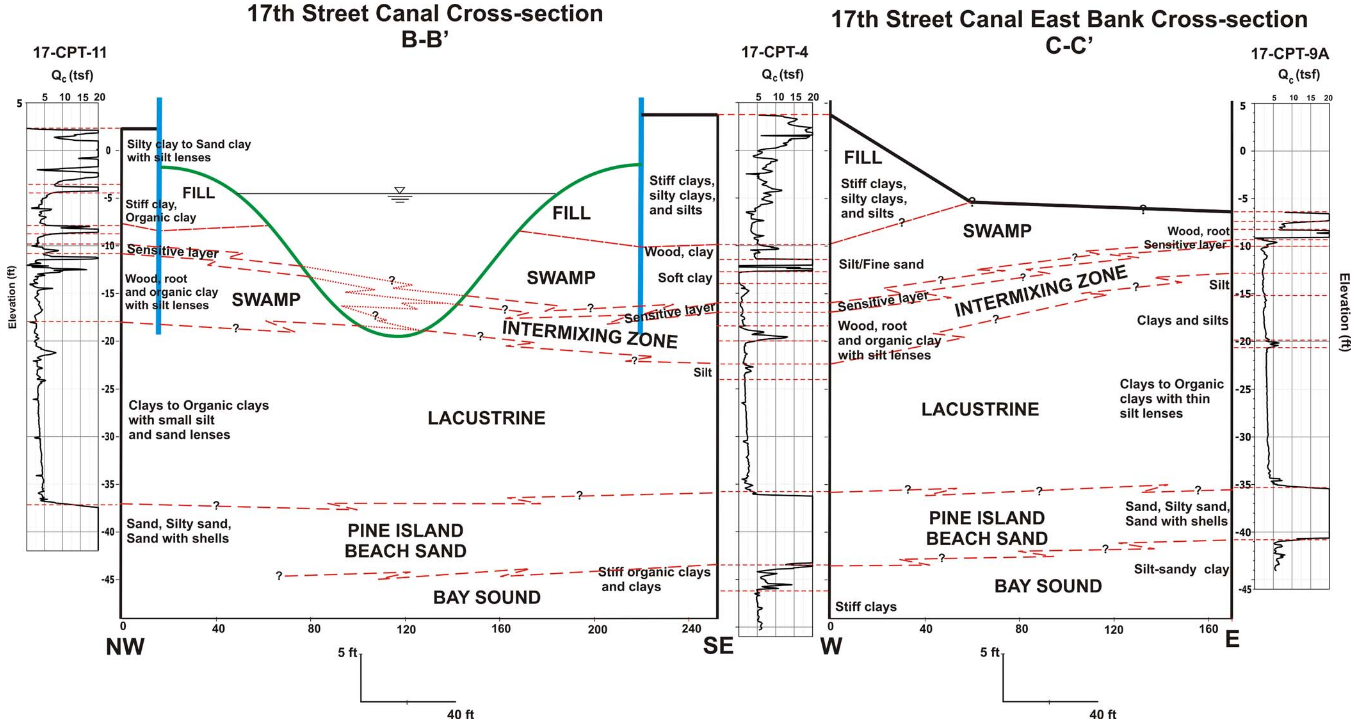

Fig. 15. Stratigraphic interpretations and cross-canal correlations in vicinity of 17th Street Canal breach on August 29, 2005. Sensitive organic silty clay caps intermixing zone. Former carries across canal, but later pinches out, as shown. Mixing zone appears to be laterally restricted, like old drainage slough. Lacustrine clay dips noticeably beneath east levee, which failed. This dip is ascribable to natural depression and primary consolidation of clay caused by levee surcharge. Positions of flood walls and canal bottom are based on postfailure surveys by Corps of Engineers (IPET 2006).

12). At the north end of the breach the flood wall fell forward (Fig. 10). Where the wall fell backward all of the sheetpile interlocks remained attached to one another.

The geology of the opposite (west) bank was relatively similar except that the organics persist in large quantities, to a depth of 11 m. The marsh deposits appeared deeper here and root tracks filled with soft secondary interstitial clay persisted to a depth of 11.9 m. Sand and shells were first encountered at 12.2 m and cohesionless sand was found at 12.5 m. This hole was terminated at 12.8 m.

Paleontology and Age Dating

Introduction

Micropaleontology was employed in conjunction with Carbon 14 (C_{14}) radiometric dating to determine both the age and depositional environment of the sediments beneath the 17th St. Canal breach. 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 these sediments suggests they were deposited in situ or were transported from a brackish Lake Pontchartrain, or from marine environments blown in by hurricanes. Palynology, the identification and study of organic-walled microfossils, commonly pollens and spores, was conducted to aid in the recreation of paleoenvironments beneath the 17th St. levees. Macrofossils of the phylum *Mollusca*, including classes *Gastropoda* and *Bivalvia*, are common in sands of the Pine Island Trend (Rowett 1957). Most recovered samples contained heavily damaged shells or fragments thereof.

Palynology

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

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 also recovered.

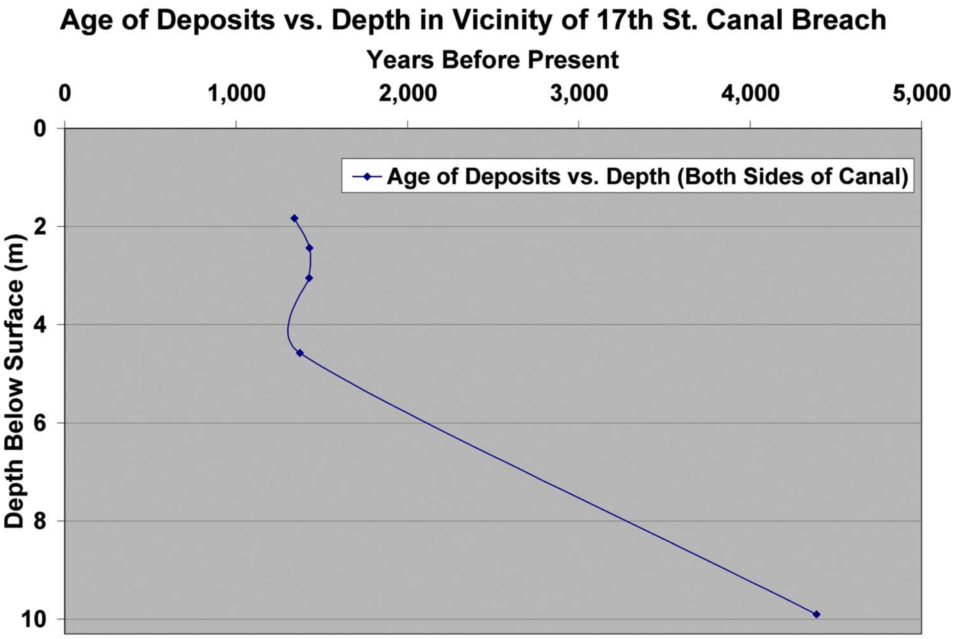

Fig. 16. Results of C_{14} radiometric age determinations made on samples of cypress wood recovered from borings adjacent to 17th St. Canal failure. These suggest rapid filling of the older cypress swamp at a depth of 4.6 to 6 m around 1,350 YBP. The oldest date came from a sample embedded in sand at −9.9 m on west (Jefferson Parish) side of 17th St. Canal.

These species were transported a considerable distance inland, indicating transport by a catastrophic event, such as hurricane storm surge or tsunami.

Foraminifera

Foraminifera were identified in the Pine Island Trend, a micaceous quartz beach sand that was deposited along the Holocene shoreline of the Gulf of Mexico by the Pearl River emanating from what is now Mississippi. This sand formed a large spit through longshore drift, creating a barrier between Lake Pontchartrain and the Gulf of Mexico (Saucier 1994). Lake Pontchartrain is a brackish body of water with only a small connection to the Gulf, through The Rigolets. 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 of a stressed environment and is not surprising, given the brackish nature of Lake Pontchartrain.

C14 Radiometric Dating

Carbon 14 dating of six samples tested by the University of Arizona NSF-funded AMS facility provides some insights into the deposition rates of the deposits underlying New Orleans in the vicinity of the 17th St. Canal breach, summarized in Fig. 16. These samples were recovered during continuous sampling in the failure area and contain cypress wood, fibrous peats, and a bivalve shell. Four samples were recovered beneath the translated section of levee on the east side of the 17th St. Canal at depths of 1.8, 2.4, 3.0, and 4.6 m below the surface. The ages of these materials are 1,341 ± 32, 1,428 ± 33, 1,427 ± 37, and 1,372 ± 33 YBP, respectively. The organic-rich sediments underlying this part of the city appear to have been deposited rapidly within the last ~1,400 years.

Two samples were recovered and dated on the west side of the failure area, where the levee and associated floodwall had been distressed, but unfailed. The organic sediments extend slightly deeper in this location. The first sample was recovered at a depth of 5.2 m below the surface and consisted of wood and organic matter, while a deeper sample from a depth of 9.9 m (32.5 ft) contained a bivalve shell. Prior to manmade developments, but in historic times, this area was a cypress swamp extending south from the shores of Lake Pontchartrain. The bivalve shell recovered at 9.9 m was incorporated in a sample of underlying sands composing the Pine Island Trend. This material provided a date of 4,388 ± 36 years before present. This date correlates with other dates of younger sediments recovered from the Pine Island Trend.

Summary and Conclusions

Subsurface data collected in postfailure forensic assessments of the 17th St. Canal levee failure in New Orleans during Hurricane Katrina corroborate well with a large body of published geologic data that were developed after 1958. A low strength horizon of organic silty clay with high sensitivity was consistently identified across the site, between the swamp/marsh deposit and the intermixing zone (on the east side), and between the swamp/marsh and lacustrine clay on the west side of the 17th St. Canal. This layer could easily be missed, due to its sensitivity, high moisture content, and a thickness of just 20 to 50 mm. The residual shear strength of this layer was found to be near zero after translating ~60 mm (Seed et al. 2007).

A check of historical records and published literature that included dozens of historic maps revealed that the drainage canals had been excavated between 1833 and 1878, and that these alignments were faithfully reproduced on each map prepared after 1858, or thereabouts. The 1872 survey by Valery Sulakowski showed the upper end of a historic drainage slough draining the historic cypress swamp in close proximity to the scene of the

2005 levee failure along the eastern side of the 17th Street Canal. Postfailure exploration revealed a somewhat anomalous intermixing zone at this same location, which dipped up to 2.5 m beneath the tips of the sheetpile bulkhead built in 1992–1993, supporting the concrete flood walls along the levee crests.

During the geotechnical exploration for the concrete flood walls in 1980–1981, three of four borings in the vicinity of the 2005 breach failed to recover any samples. A fateful decision was made to linearly extrapolate the presumed stratigraphic contacts between the next adjacent borings that recovered samples, covering a distance of 610 m (2,000 ft). Sheetpile tip elevations were based on the assumed depth of the contact between the swamp materials and the lacustrine clay, extending 0.6–1 m beneath the assumed horizon. This assumption appears to have been well founded, except in the vicinity of a natural depression, about 100 m wide.

There are some fundamental lessons to be drawn from this study. Unfortunately, those lessons are not new, but have plagued geotechnical practice since its inception. Briefly stated, these lessons are as follows:

1. Never use ruler straight lines to represent naturally deposited systems. There is no such thing as a ruler in geology. Settlement and consolidation always occur after deposition or planation, and the process of water expulsion is seldom linear or uniform, but tends to promote an uneven or undulatory surface. Any hiatus between sequences of deposition can be expected to produce some unevenness, due to local erosion.
2. Always demand the privilege to redrill and resample holes bereft of sample recovery, whatever the cost or consequences. It is the weakest materials that typically defy sampling, but are crucial to accurate site characterization.
3. In areas exhibiting complex stratigraphic relationships, it is usually advisable to construct multiple cross sections with vertical exaggeration in order to catch channels and other natural depressions. Cross sections without vertical exaggeration are necessary to ascertain loading and reaction geometries with respect to structures, such as bulkhead walls. This is particularly critical in foundations containing discrete layers of high sensitivity, low strength, stiffness contrasts, or overconsolidated clays subject to strain softening behavior. If the geometry of such horizons coincides with passive reaction wedges developed adjacent to embedded structural elements, this condition can have disastrous results, such as those which occurred along the eastern side of the 17th Street Canal, well below the design level of the recently constructed flood walls.
4. When analyzing slope stability, never allow averaging of soil shear strength, especially along seemingly thin, or discontinuous horizons. The lowest value of the weakest horizon (s) will tend to dominate future performance.

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