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Katrina's unique splay deposits in a New Orleans neighborhood

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Katrina's unique splay deposits in a New Orleans neighborhood

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ABSTRACT

On 29 August 2005, storm surge from Hurricane Katrina entered the drainage canals in the northern part of the city of New Orleans, Louisiana, USA. Although the floodwalls and levees on these canals were not overtopped, the surge resulted in three levee breaches that flooded 80% of the city. The southern breach on the London Avenue Canal resulted in a blast of water that displaced a house in front of the breach and buried parts of the neighborhood with up to 1.8 m of sandy sediment derived from remobilization of subsurface late-Holocene marsh and beach deposits. These deposits are a rare but spectacular example of crevasse splay deposits in an urban environment. Approximately 26,380 m^3 of material, varying in size from fine sand to gravel-size clay balls, along with various human-made objects, was deposited mostly as planar strata, with some small- and medium-scale cross-strata showing climbing bed forms that were deposited on and around obstacles, such as cars and houses. This unique splay deposit has no preservation potential, and this paper reports the first (and probably only) results from the study of its morphology and sedimentology.

INTRODUCTION

On the morning of 29 August 2005, Hurricane Katrina made landfall to the southeast of New Orleans, Louisiana, USA, as a Category 3 hurricane (Knabb et al., 2005). Levees along the New Orleans Industrial Canal, which connects the Mississippi River to Lake Pontchartrain, were overtopped and breached by 7 a.m. central daylight time, resulting in flooding of areas north of the French Quarter (Fig. 1). A catastrophic failure of the floodwall and levee on the eastern side of the canal devastated the Lower Ninth Ward. Over the next few hours, as the hurricane moved inland, the storm surge from Lake Pontchartrain entered canals designed to drain the city of rainwater, resulting in the catastrophic failure of levees at three locations, two on the London Avenue Canal and one on the 17th Street Canal (Fig. 1; see animation from *The Times-Picayune* at www.nola.com/katrina/graphics/flashflood.swf). The failures occurred before the maximum surge level had been reached. Eighty percent of the city of New Orleans was flooded to depths up to 4.6 m due to these floodwall and levee failures.

Three weeks later, after the floodwaters had been pumped out, sand deposits were revealed to have covered the neighborhoods near the breaches of the London Avenue Canal. These deposits will not be preserved and, in fact, have mostly been removed as part of the clean-up effort. We were, however, able to observe the deposits soon after their deposition (from aerial photographs) and during the removal process (from field work). This paper focuses on this rare but spectacular example of splay deposits in an urban environment, describes the distribution of these deposits and their physical features, and compares them with modern natural splays.

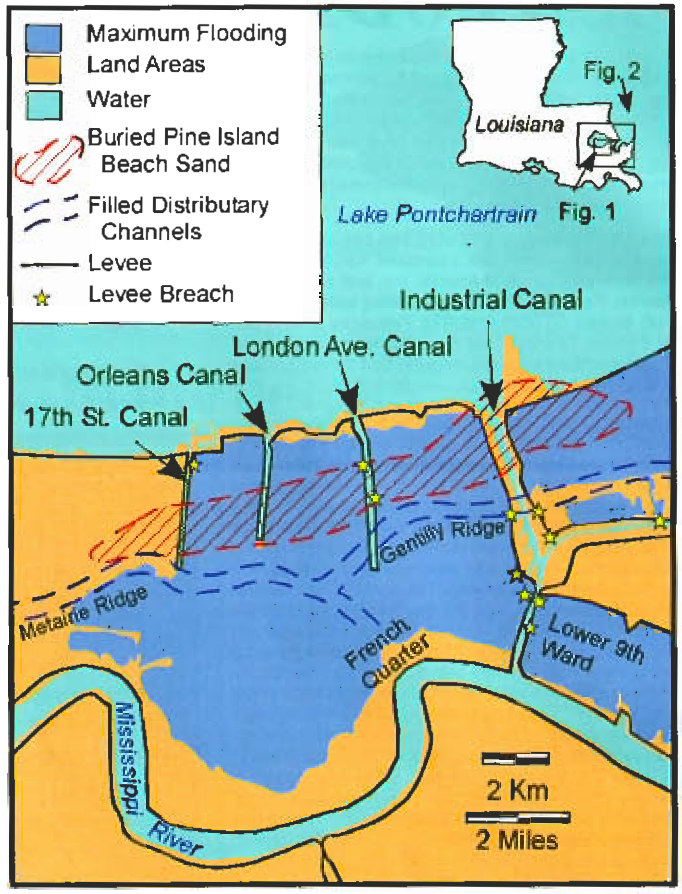

Figure 1. Map of the New Orleans area showing the maximum extent of flooding from levee breaches on 29 August 2005 (based on information from the U.S. Army Corps of Engineers, 2006), the locations of the drainage and navigational canals, breaches on these canals, and the extent of the levee system. The approximate area where the Pine Island sand lies below the surface and the locations of the late-Holocene St. Bernard Delta distributary channel fills that make up the Metairie and Gentilly ridges are also shown (modified after Snowden et al., 1980).

GEOLOGICAL SETTING AND HISTORY OF STUDY AREA

In order to explain the origin of the levee-breach deposits, we first discuss the geological and historical setting of New Orleans. Five thousand years ago, the future location of New Orleans was offshore of the southern coast of this part of North America (Otvos, 1978; Snowden et al., 1980; Fig. 2A). As sea level rose due to the continuing melting of continental glaciers, longshore currents produced a sand spit extending from what is now southwestern Mississippi toward the present-day location of New Orleans (the Pine Island Trend in Fig. 2B). At about the same time, the Mississippi River began building the

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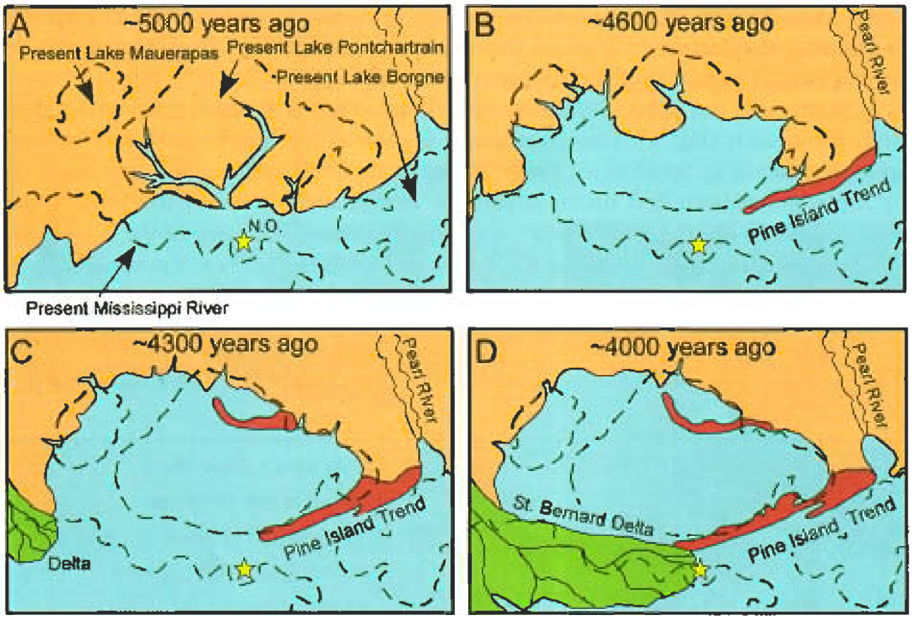

Figure 2. Development of the Pine Island Trend as sea level rose between 5000 and 4000 yr ago. Dotted lines indicate the current locations of Lakes Maurepas and Borgne and the present trace of the Mississippi River. See insert in Figure 1 for regional location. (A) Site of New Orleans (yellow star) was offshore; (B) a sand spit developed; (C) St. Bernard Delta began building eastward; (D) growing St. Bernard Delta reached and buried the sand spit, resulting in the formation of Lake Pontchartrain (modified from Otvos, 1978; Snowden et al., 1980).

St. Bernard delta complex eastward (Figs. 2C and 2D), eventually burying the Pine Island Trend beach sands (Fig. 1; more on the evolution of the Mississippi River delta lobes can be found in Coleman et al., 1998, and Aslan et al., 2005). Drainage from the north was thus cut off to enclose what would become Lake Pontchartrain (Fig. 2D). About 2000 yr ago, the Mississippi River shifted its course back to the southwest of New Orleans and abandoned the St. Bernard distributary channels, some of which were filled to become what are now Metairie Ridge and Gentilly Ridge (Fig. 1). The Mississippi River shifted its course back to its present-day position ~1000 yr ago, and New Orleans was founded on the natural levee of one of its meander bends in 1718. By the late 1800s, the city had spread along the ridges of the former distributary channels, with cypress swamps in between the populated zones. In the early 1900s, pumps were built to drain rainwater into Lake Pontchartrain (~0.6 m above sea level [asl]), and later to drain the swampy areas, providing more habitable land for the growing city (more details in Nelson, 2006). The London Avenue, Orleans, and 17th Street drainage canals normally contain water at the elevation of Lake Pontchartrain and run between levees with elevations of ~1.1 m asl. These levees are capped by concrete floodwalls, built in the 1990s, that rise to an elevation of 3.9 m asl. Katrina's storm surge pushed water from the lake into the canals up to 2.5 m asl; hence, the floodwalls were not overtopped. Yet the levees and floodwalls failed at three locations (Fig. 1). The neighborhood immediately surrounding the southern breach of the London Avenue Canal is at elevations between 1.4 and 1.9 m below sea level (bsl); that is, at as much as 2.5 m below the maximum water level attained in the canal during the storm.

A geological cross section of the east bank of the London Avenue Canal, based on soil borings conducted prior to the construction of the floodwall, is shown in Figure 3 (Eustis Engineering, 1986; U.S. Army Corps of Engineers, 1989). A former distributary-channel fill that

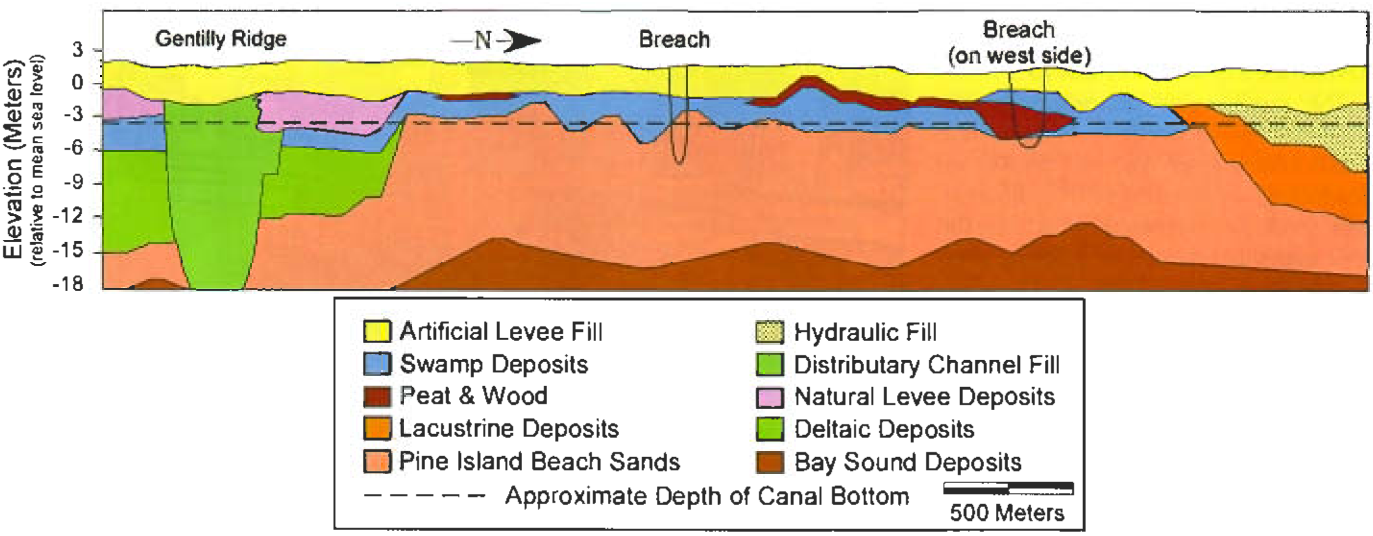

Figure 3. Geological cross-section along the east bank of the London Avenue Canal (Fig. 1), based on soil borings from Eustis Engineering (1986) and the U.S. Army Corps of Engineers (1989). Units pertinent to the study are described in the text. Hydraulic fill consists of lacustrine deposits (silty clay and clayey silt) that were pumped from the bottom of Lake Pontchartrain in the 1940s to build the land area northward into the lake.

forms the Gentilly Ridge occurs at the southern end of the cross section. The artificial levee fill consists mostly of clays with pockets of sand, silt, and occasional logs and shells. The levee fill overlies a 1.5–3-m-thick layer of organic-rich clays that contain peat and wood fragments (particularly at the northern end of the canal under the west-side breach, Fig. 3), consistent with deposition in the swamp that was present here prior to ~100 yr ago. Underlying the swamp deposits, and cut by the deltaic sediments at the south of the cross section, are the 9–12-m-thick Pine Island Trend beach deposits (Fig. 3). These deposits, which consist of fine-grained sand, shells, and shell fragments, have been observed mostly in the subsurface throughout the northern and eastern portion of New Orleans (Fig. 1; Snowden et al., 1980; Miller, 1983). In our study area, the base of this beach sand overlies the fine silty clay deposits of an ancestral bay-sound (Miller, 1983) at elevations ranging from 13 to 17 m bsl. The canal bottom is 3.7 m bsl (Fig. 3). The levee breaches on the London Avenue Canal occurred along stretches of the canal where the Pine Island Trend sands are at or within 2 m below the canal bottom. Although it is beyond the scope of this paper to discuss the causes of the levee breaches, the current consensus is that hydraulic piping through the sand toward the neighborhood side of the levee resulted in a blowout and catastrophic failure (Seed et al., 2006; U.S. Army Corps of Engineers, 2006).

EXTENT AND MORPHOLOGY OF KATRINA'S SPLAY DEPOSITS

The sandy splay deposits near the southern breach of the London Avenue Canal covered an area of ~54,670 m^2 (excluding areas occupied by houses), with a volume, estimated by dividing the area into small parcels of differing average thickness, of ~26,380 m^3. The splay originated from a ~61-m-long breach that occurred between 7 and 8 a.m. on 29 August 2005 (Seed et al., 2006). Repairs started two days later, after the water in the neighborhood stabilized at the level of Lake Pontchartrain (U.S. Army Corps of Engineers, 2006). The variation in flow direction, depth, and velocity prior to the start of repairs is not known because there are no known eyewitnesses. Still, the initial torrent of water from the breach was powerful enough to remove a house from its concrete foundation, displacing it ~35 m to the east and rotating it ~137° counterclockwise before it came to rest after running into a tree (Fig. 4).

In plan view, the splay deposit shows elongate lobes spreading up to ~400 m from the breach (Fig. 4). This plan shape is clearly different from that of natural splay deposits (e.g., Smith et al., 1989; Gomez et al., 1997), because it was influenced by the street pattern and urban structures. Immediately north of the breach, the flow deposited up to 1.8 m of sand in the backyards and in front of the houses on Warrington Drive (Fig. 4). Along the backyards of these houses, the sand surface shows two ridges parallel to each other and to the canal (Fig. 5A). No sediment was deposited along some driveways between houses (Figs. 4 and 5B), but sand

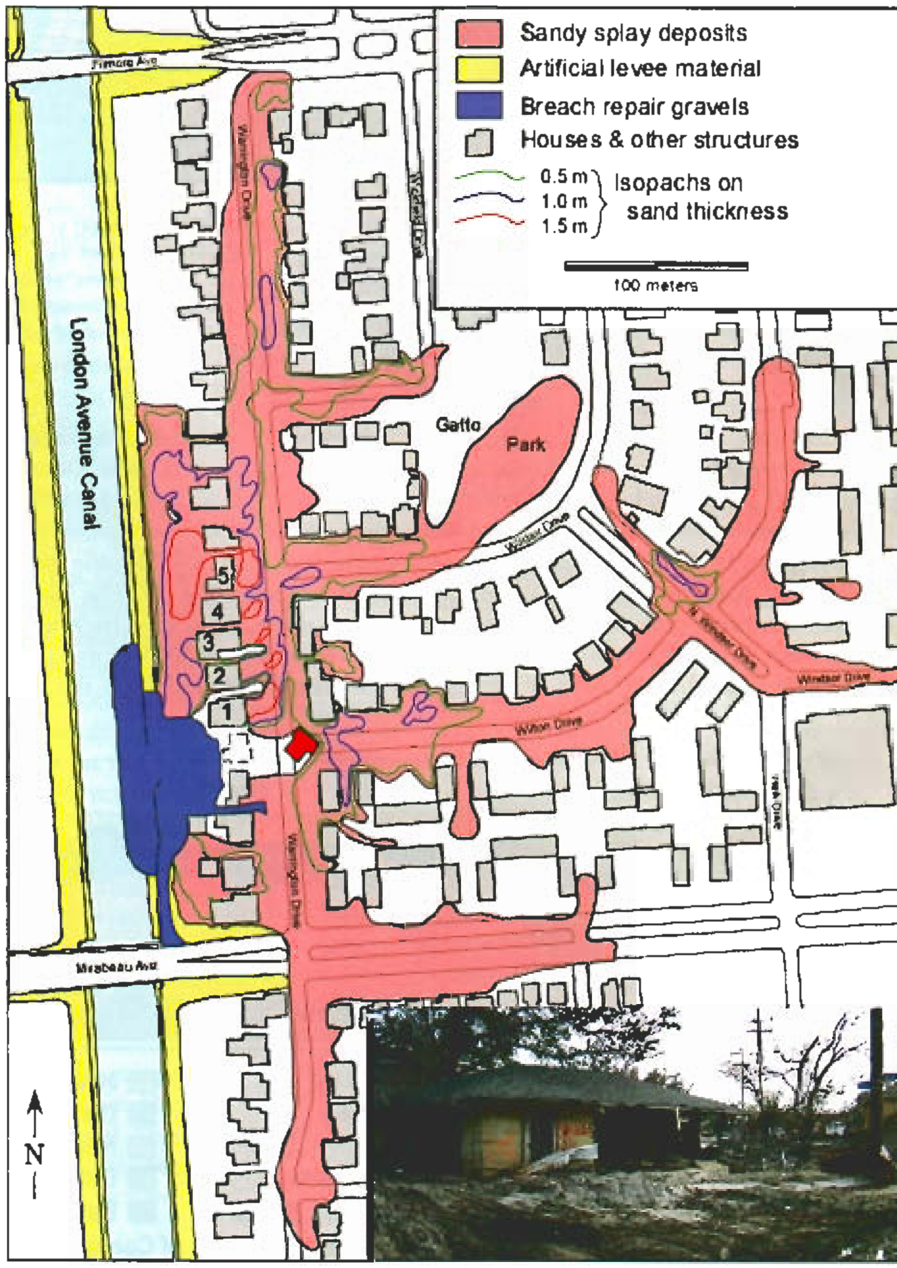

Figure 4. Map, based on field work, showing the distribution and thickness of the sandy splay deposits in the area around the southern breach of the London Avenue Canal. Houses referred to in the text and other figure captions are numbered. Displaced house indicated in red and shown in inset.

buried vehicles in the front yards (Fig. 5C) and was deposited within houses near the breach (Fig. 5D). Sand was also deposited along the streets intersecting Warrington Drive, with thicknesses up to 1 m (Figs. 4 and 5E). The most distal parts of the splay were <0.3 m thick, and hence the gradient of the deposit's upper surface is nearly 0.004.

Figure 5. Photographs of sandy splay deposits. Refer to Figure 4 for locations. (A) View from backyard of house no. 5, looking south toward the breach; there are two ridges of sand, parallel to flow direction, with a maximum thickness of 1.8 m. (B) Driveway between houses no. 2 and no. 3, with absence of sand along the red brick house, and the open garage across the street where the flow ran through it. (C) Roofs of cars protruding through the sand deposit in front of house no. 5. Note the holes in the house's roof that were used as exits for residents escaping the floodwaters. (D) Sand deposits in the kitchen of house no. 2. Note the water lines on the walls that resulted from three weeks of standing water. (E) View from Wilton Drive, looking west toward the levee breach; sand deposits on the right; displaced house shown below the trees in the middle distance; and brown temporary sheet piling levee repair in the far distance.

SEDIMENT AND SEDIMENTARY STRUCTURES

Much of the sand in the streets near the breach was cleared by late December 2005, providing the initial vertical exposure of the deposits. By late February 2006, front yards were entirely cleared, creating exposures along the front of the houses. Although the deposit looked mostly sandy from its surface (Figs. 5A, 5C, and 5E), it contained an appreciable quantity of mud (e.g., dark layers in Figs. 6 and 7), ranging from gravel-size mud clasts >500-mm in diameter to sand-size pellets. Organic material (also of dark color) within strata consisted of leaves and twigs a few millimeters long. Numerous gravel-size clay balls were observed throughout the vertical profiles on Warrington Drive (Figs. 6 and 7A). The sand fraction in all parts of the splay deposit consisted of fine sand (0.125–0.25 mm). Along Warrington Drive, backyard deposits contained less mud than their front-yard counterparts. Various marine shells were found within the strata, typically mollusks from shore-face barrier islands (Hollander and Dockery, 1977), and the largest shells (~10 cm across), mostly found unbroken, were those of *Dinocardium robustum* (Fig. 7A). As no sand occurs in the breached levees, it is clear that the sand originated from the buried Pine Island beach deposits in the subsurface (Figs. 1 and 3).

Overlying a massive clayey-sand layer (Fig. 6), planar strata were dominant and continuous throughout the street exposures on Warrington Drive, interrupted occasionally by objects of various sizes (e.g., pencils, clothes, or window blinds). Low-angle strata (Fig. 7B) reflected the shape of the ridge surfaces (Fig. 5A). Medium-scale cross-strata overlay planar strata only along Warrington Drive (Fig. 7C), and small-scale cross-strata were largely absent, except in protected areas, such as house porches (Fig. 7D). Spectacular cases of climbing dunes were seen on obstacles, such as cars, which were in most cases resting on a layer of sand and not directly on the ground, as if they had been floating for some time. Cross-stratification around obstacles indicates different flow directions (Fig. 7D). In open areas, the upper part of the deposit was composed of fine sand and organic material, such as leaves

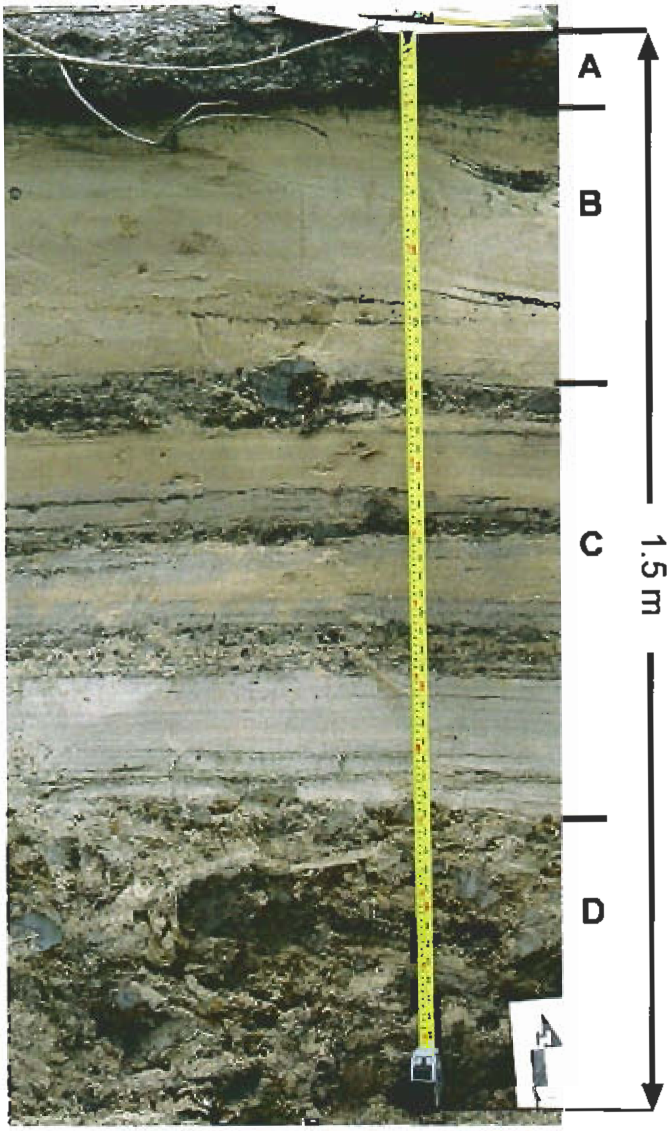

Figure 6. Vertical section of deposit along the west edge of the street in front of house no. 2 (Fig. 4). (A) Organic material consisting of leaves and twigs. (B) Medium-scale cross-strata sets (~10 cm thick). (C) Planar strata; some layers mostly sandy, others with clay balls and concentration of mud and organic material. (D) Massive layer composed of sand and several gray mud balls. The base of the deposit was 10 cm below shown section, in standing water.

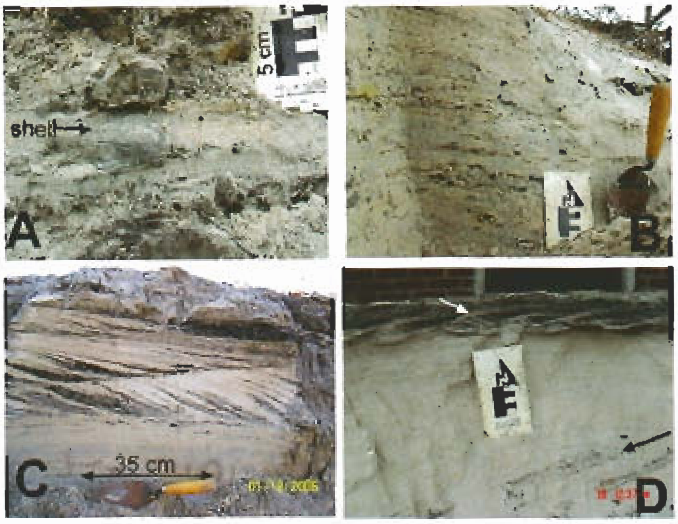

Figure 7. Sedimentary structures in the sand deposits: (A) between house nos. 3 and 4 (see Fig. 4), clay balls and mollusk shell (arrow) in sands; (B) behind house no. 5, low-angle planar strata in ridges, dipping to the right (toward canal); (C) in front of house no. 1, medium-scale cross-strata sets overlying planar strata; darker material consists mostly of a wide size range of clay pellets; and (D) on front porch of house no. 3, climbing-ripple cross-strata (white arrow) over fine-grain planar strata and coarse-grain medium-scale cross-sets (~50 cm thick; black arrow).

and twigs, with no apparent lamination. Away from Warrington Drive, planar strata were observed at ground level, although the thicker deposits at the corner of Wilton and Windsor drives (Fig. 4) showed low-angle cross-strata at their base.

DISCUSSION

There are no descriptions of urban splay deposits with which to compare those described here. Natural (Coleman, 1988; Bristow et al., 1999; and many others [see Bridge, 2003]) and intentional splays (e.g., those created to restore floodplain ecology: Barmore, 2003; Boyer et al., 1997; Florsheim and Mount, 2002) all occurred away from towns. If they existed, deposits from past levee failures in urban environments surely would have been removed and therefore could not be mapped in studies of surficial materials (e.g., Vink, 1926; Berendsen, 1982). Similarly, little remains of the sand in our study area.

The most obvious feature of this splay is that its geometry was controlled by the distribution of houses and streets. The levee-breach flow was either erosional or depositional, depending on whether the urban structures caused the flow to converge or expand, respectively. Erosion was evident near the breach, with displaced and damaged structures (Fig. 4), but the spaces between houses on Warrington Drive also created high flow-velocity zones capable of transporting all available material (such as along the "clean" brick wall in Fig. 5B). Elsewhere in the neighborhood, streets also acted as channels, with deposits commonly thicker on just one side of the street (e.g., Fig. 5E) or where the channel expanded, such as at street intersections or at Gatto Park on Wildair Drive (Fig. 4).

The most conservative estimates of sediment deposition rates at any part of this splay deposit (0.3 m to 1.8 m in two days) are notably higher than values previously reported for natural (an average of ~1.5 m/yr in Ethridge et al., 1999) and intentional splays (0.36 m/yr in Florsheim and Mount, 2002), where deposition occurred over a much longer time period. The maximum thickness of this deposit was observed within 125 m of the breach (Fig. 4), and not along a horseshoe-shaped rim, such as in the Sny Island levee break of the 1993 Upper Mississippi Valley flood, where the rim of maximum thickness occurred ~800 m from the levee break (Gomez et al., 1997). Flow from the Sny Island break, however, was not interrupted by urban structures, as was the case at the London Avenue Canal. The margins of the London Avenue deposit did not show avalanche faces, as in some modern crevasse splays (Bridge, 2003), but ended with gently dipping sand lobes. This suggests that the sediment at the splay margin may have been reworked while the water level in the neighborhood was adjusting to that of Lake Pontchartrain.

The fact that planar strata is the dominant sedimentary structure throughout the exposures indicates that an upper-stage plane bed, and hence an upper flow regime, prevailed during most of the deposition. Decimeter-thick cross-beds formed by dunes or sand bars only occur around obstacles where flow was decelerated and its direction diverted (e.g., Fig. 7D). The lack of small-scale cross-strata formed by ripples suggests that very little deposition from slow-moving currents occurred and that flow velocity decreased rapidly in time. These sedimentary structures are somehow different than those observed in modern sandy crevasse splay deposits, where, although planar strata is very common, climbing-ripple cross-strata and medium-scale cross-strata (from dunes) are also commonly observed at the top and in crevasse channels, respectively (Bridge, 2003).

The volume of this deposit and its composition, which includes a large fraction of fine sand, and the occurrence of gravel-size clay balls and marine shells, indicate that the main source of material was neither Lake Pontchartrain nor the levees. The canal bottom was in the Pine Island beach sands, and thus the sediment deposited in the neighborhood was derived essentially by scour from the canal bottom and beneath the failed portion of the levee (Fig. 3). At the immediate site of the breach, engineers working on repairing the levee have stated that the depth of scour extended to 6.1 m bsl, or ~7.6 m below the surface. This scour depth is shallower than the 22 m reported by Vink (1926) in the Rhine-Meuse delta but still much deeper than the typical range observed in natural and intentional breaches on the Mississippi River (<2 m in Gomez et al., 1997) and its delta (1.5 m to 2.4 m in Boyer et al., 1997). Assuming the area occupied by the breach is ~1022 m^2, the estimated volume of the hole is ~7800 m^3, or only ~29% of the volume of the splay deposit. Therefore, a significant amount of scour must have occurred on the bottom of the canal. This raises concerns regarding the stability of the New Orleans drainage canal levee system, considering the extent of the Pine Island sands in the subsurface beneath all of the drainage canals (Fig. 1). Scouring immediately downstream of overtopped levees and upper-bank breaches is common, mostly in easily erodible sandy material (e.g., Aslan et al., 2005), yet scouring from beneath the levee requires a particular geological setting. In the Netherlands, where the channels of the Rhine-Meuse River system have been embanked—and breached—since ~1100 A.D., several cases of splays have been correlated with sandy channel belts in the subsurface (Fig. 8); these sandy belts promote groundwater flow during high-discharge events, which can undermine the levees and ultimately cause them to collapse (Berendsen, 1982). A similar mechanism has been proposed for the London Avenue Canal breach (Seed et al., 2006; U.S. Army Corps of Engineers, 2006).

CONCLUSIONS

Analysis of the morphological and sedimentological characteristics of the London Avenue splay deposit provides an understanding of the magnitude of the levee breach in one New Orleans neighborhood. The flow was either erosional or depositional depending on the spatial distribution of urban structures, which either helped to confine or expand the many

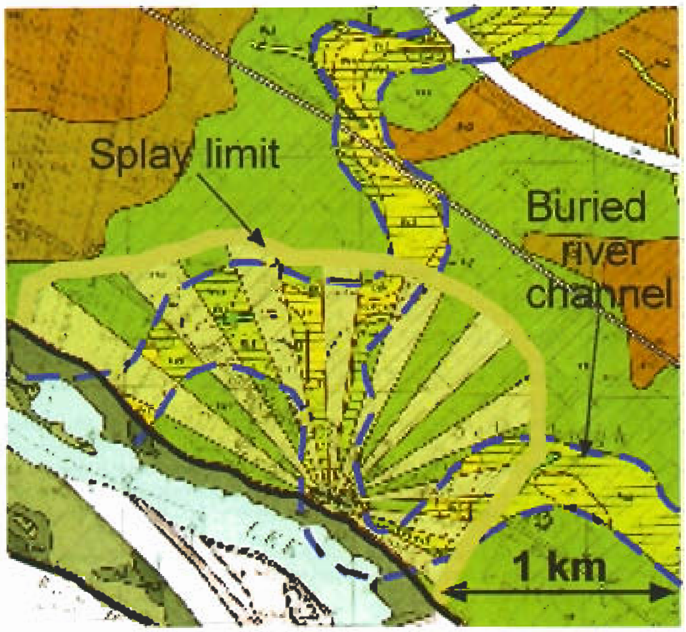

Figure 8. Details of the map of surficial materials of the Rhine-Meuse Delta in the Netherlands, showing typical plan view of a crevasse-splay deposit. Location of sandy river channel is indicated in blue dashed line. Note that breach and origin of splay occurred where levee intersects buried channel. Modified from Berendsen (1982).

intersecting currents. Most of the deposition, up to 1.8 m of sandy material, probably occurred in a short time period from an upper-stage plane bed, and there was little reworking of sediment. This urban splay deposit has no preservation potential and has, in fact, mostly been removed. The only evidence that remains are the data reported here and in future publications of various groups that are currently investigating the Katrina disaster.

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We send our most sincere thoughts to all the people who suffered from Katrina, particularly to the New Orleanians who lost their lives in this neighborhood, as well as to those whose homes provided accommodation space to this sadly unique splay deposit. We would like to thank Torbjörn Törnqvist for bringing to our attention some levee-breach examples from the Dutch literature (and for translating excerpts of dissertations) and Rebecca Freeman for interesting discussions on paleo-environments in this study area. We are thankful to John Bridge, Jim Coleman, and John Southard for their thoughtful reviews and for editorial comments from Gerry Ross.

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TO READ MORE about studies in this area, see the **August *Geology*** article by Törnqvist et al. (v. 34, p. 697–700, doi: 10.1130/G22624A.1), "How stable is the Mississippi Delta?"