Hurricane Katrina Splay Deposits: Hydrodynamic Constraints on Hyperconcentrated Sedimentation and Implications for the Rock Record

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Abstract

A breach of the London Avenue Canal levee in New Orleans' Lower Ninth Ward during Hurricane Katrina created a unique opportunity to compare flow conditions with the resulting bedforms. Those deposits are examined and correlated to probable hydrodynamic conditions during deposition, including the fluctuating causes for repetitive bedforms and changing conditions within the continuous unidirectional current through the breach. Flow depth was determined mathematically from clast size and is examined as a limit on bedform thickness. Characteristics of the splay deposits point to deposition under hyperconcentrated conditions in a high-velocity current, leading to a remarkably high depositional rate. This study suggests a mechanism for the simultaneous deposition of multiple laminae as a single set under hyperconcentrated conditions. Clay and clay drapes in the deposit indicate fluctuations in flow, not a cycle of active/passive sedimentation.

Introduction

The interpretation of sedimentary rocks and their bedforms has been at the heart of geology since its inception, because the features of rocks provided an open door to speculation about their origin. Early attempts were largely qualitative, centering around speculative assumptions of the presumed paleoenvironment. Each environmental setting became identified as a facies, and their description was driven by assumptions such as deep time and strict uniformitarian rates of progress. The advent of quantitative sedimentology, with its basis in physics rather than environmental constraints, has provided an alternate means of understanding features on many scales, though the stratigraphic placement in the geologic column and the associated paleoenvironmental paradigm has continued to constrain most contemporary interpretations.

Today, with decades of investigation—largely driven by fluid mechanics—sedimentologists are applying mathematical precision to many aspects of sedimentary rocks, using physical properties of the grains and their bedding to derive flow velocity, depth, and other diagnostic features. Sedimentary bedforms, because they persist in the rock record, have provided a means to work from bedforms and grain characteristics to mathematically derive likely environmental factors such as velocity, flow

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depth, concentration, and the rate of deposition under the original conditions.

Quantitative sedimentology is hard science; it provides an invaluable forensic tool to help us understand the past. The detailed study of modern examples, in nature and in the laboratory, provides constraints on interpretation. McLane (1995, p. 84, parentheses in original) noted that, "Sedimentary structures (in conjunction with body fossils, if they exist) constitute the major evidence in our diagnosis of depositional environments." Bedforms, especially at the millimeter to centimeter (mm to cm) scale, offer an opportunity to ascertain the processes and energy relationships that create them. A recent example of an unusual event was the splay deposits created by levee breaches in New Orleans during and after Hurricane Katrina. These demonstrated a cause-and-effect link between well-constrained fluid/sediment interactions and their bedforms. A close study of these deposits is valuable because they provide application to splay deposits, sedimentary processes in the high-energy environment of a hurricane, and complex hydrodynamic processes applicable to the rock record.

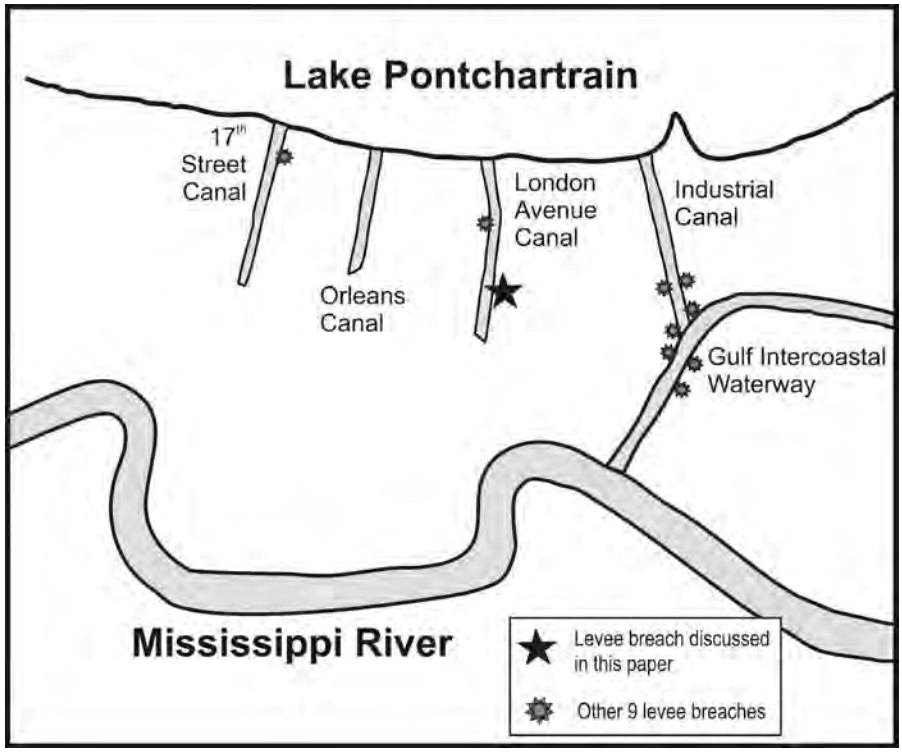


Figure 1. Map of New Orleans showing locations of levee breaches and the breach studied in this paper.

New Orleans was settled during the 1700s on a natural levee of the Mississippi River north of Lake Pontchartrain. As the terminus for Mississippi River trade, by the early 1800s, the city had expanded into the low-lying swampland between the river and lake. Some of this converted swampland lay up to -1.9 m (-6.2 ft) mean sea level (msl) and 2.5 m (8.2 ft) below lake level, normally 0.6 m (2 ft) above sea level (Nelson and Leclair, 2006). Over the years, a series of levees were constructed along the river and lake, and canals provided shipping lanes between the lake and the river. Other drainage canals extend from largely residential areas of the city into the lake (Figure 1). All modern levees exceed the lake water level and are capped by a concrete flood wall rising an additional 1.4 m (4.6 ft) above lake level, or 2 m (6.6 ft) above msl. The Lower Ninth Ward and the lakefront area drained by the London Avenue Canal are typical of areas built on low-lying swampland.

Geologically, much of the city rests on channel fill and delta deposits of the Mississippi River referred to as Gentry Ridge (Nelson and Leclair, 2006). A prominent body of mature white sand, the Pine Island Beach Sands (PIBS), underlies both Gentry Ridge deposits and lower-lying residual swamp deposits (RSD), on which residential areas from the lake to the Lower Ninth Ward were built (Eustis Engineering, 1986). The PIBS is believed by Nelson and Leclair (2006) to be an old sand spit created by east-west longshore Gulf of Mexico currents (Figures 2 and 3). These sands lie between Lake Pontchartrain and the present-day gulf, deposited in similar fashion to Dauphin Island off the coast of Alabama (Froede 1995).

Following Katrina, researchers investigated the causes of the flooding. Two of the most prominent studies were completed by Louisiana State University and the University of California, Berkeley. During the cleanup effort, a team from Tulane University mapped and photographed the sediment surfaces and some of the cross sections in the area of the southeast breach of the London Avenue Canal (Nelson and Leclair, 2006, their figure 4). Research was ended by the rapid cleanup of flood sediments and the absence of direct eyewitness accounts of the relevant flooding, but photos and reports provide a surprisingly complete record for evaluation of the sedimentation during levee breaches (Nelson and Leclair, 2006). This paper will focus on the southeast London Avenue Canal levee breach, photographed and described in the Tulane report (Nelson and Leclair, 2006).

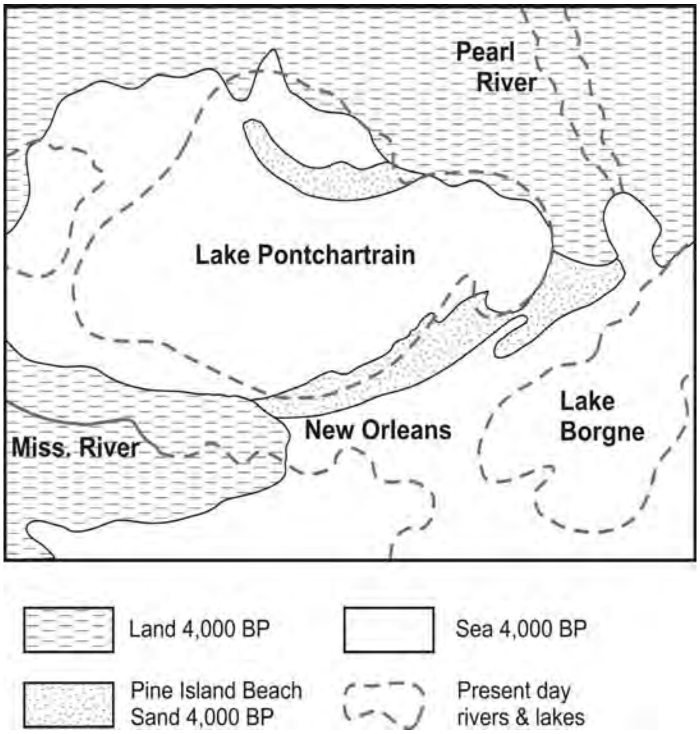
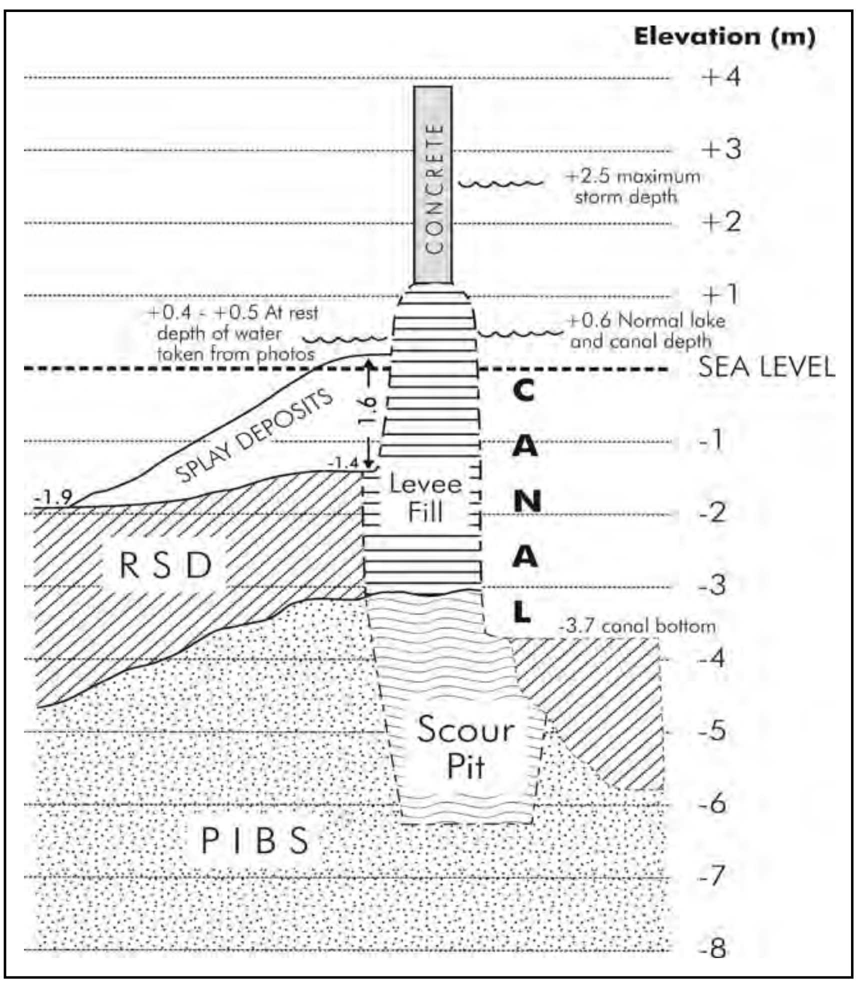


Figure 2 *(left)*. Probable configuration of Pine Island Beach Sand in relationship to land and sea in 4,000 BP. Two sand spits developed from east-west longshore currents. The northern one is now under Lake Pontchartrain, and the second underlies much of New Orleans and St. Bernard Parish. After Nelson and Leclair (2006, figure 2).

Figure 3 *(below)*. East to west cross section of land and canal elevations adjacent to London Avenue Canal levee showing comparative heights. Splay deposit height of 1.6 m used for comparison of wave and flow depth at measured cross section. All elevations relative to sea level.



Correlation of maps, cross sections of sediments, and published descriptions of the conditions allow a detailed understanding of the hydrodynamic processes and the bedforms they produced. The levee breach can be viewed as a natural-scale flume experiment, at a scale unavailable in the laboratory. The Katrina splay deposits were produced by the interaction between sediment source, water surface gradients, winds, waves, currents, current pathways, and local obstructions. This study is significant because it provides sedimentological constraints on bedforms observed in the rock record. Specifically, it demonstrates that several sequences of bedforms previously interpreted as indicating long periods of time, can be formed in a matter of minutes. Thus, understanding these deposits and their physical causes will better constrain interpretation of much larger, but similar, features found in strata (Reed and Froede, 2009).

Hurricane Katrina and the New Orleans Canal Breaches

Hurricane Katrina made landfall over Florida, regained strength in the Gulf of Mexico, and curved northeast to strike the Louisiana and Mississippi coasts. It crossed New Orleans and the adjacent St. Bernard Parish at about 6:10 am, CDT on 29 August 2005, as a Category 3/4 hurricane, with sustained winds of over 205 kph (125 mph) (Knabb and Rhone, 2005). At 8:14 AM CDT, the National Weather Service issued a flash flood warning for New Orleans and St. Bernard parishes, citing a levee breach on the Industrial Canal (Place of Dead Roads, 2005). This breach appears to have been caused by overtopping of the levee wall by a storm wave up to 7 m (23 ft) high, moving up the Gulf Intracoastal Waterway (Figure 1). The wave apparently struck the levee wall broadside (Seed, 2005). The levee failed, and its breach was quickly enlarged. Within 46 minutes, by approximately 9:00 AM CDT, the Lower Ninth Ward was reported to be inundated by 1.8–2.4 m (6–8 ft) of water (McQuaid, 2005a).

Initially, residents of lakefront areas of Lake Pontchartrain and those of other parts of the city, away from the larger shipping canals (Figure 1), thought they had escaped. None of the levees bordering the 17th Street Canal, the London Avenue Canal, or Lake Pontchartrain were ever reported as being overtopped by the storm surge. This may be because the lake, not being open to the gulf, did not propagate waves of sufficient size. However, other factors caused several additional levee failures throughout the city. Homeowners near the 17th Street Canal had previously reported water seeping into their yards (Marshall, 2005). Berkeley researchers attributed the catastrophic failure of the 17th Street Canal and the London Avenue Canal levees to erosive undermining in the RSD and PIBS (McQuaid, 2005b; Nelson and Leclair, 2006).

Water gushed through these breaches until the elevation head of the flooded areas equalized with the lake. That head pressure created flow through the breaches sufficiently powerful to dislodge and move a house. As the pressure difference decreased, flow velocity diminished. The lateral extent of the highest velocity was quite restricted; strong at the breaches—as indicated by the erosional absence of sediments—and weaker moving away. Resulting areas of erosion and deposition were observed after the floodwaters were pumped back into the canals. Nelson and Leclair (2006, their figure 5b) provided a pre-cleanup photo of the passage between the second and third houses north of the breach and the bare ground between them covered with grass. Although sand in the street was still more than waist deep, no significant sediment was ever able to settle in this area. As the current began to disperse and wane, sediment was deposited in mounds, often dictated by local obstructions, as the current shifted from supercritical to subcritical flow.

Subsequent action by counter currents, wave action, or pumping was insufficient to substantially alter the initial depositional/erosional patterns. This suggests that (1) maximum deposition and the resulting bedforms were produced very rapidly—within a maximum of the 46 minutes required to equalize the elevation head in the Lower Ninth Ward—and (2) deposition of the sediments and creation of bedforms was continuous, as was the flow. Deposition of bedforms occurred only while the current was at its highest velocity, flowing outward from the canals. Bedforms were not significantly altered during the subsequent three-week inundation or later pumping. Thus, the observed form and sequence of bedforms reflects the hydrodynamics of the breach—a high-velocity, unidirectional current. Understanding the current's direction, speed, consistency, and duration provides significant hard data for interpreting its sedimentary products.

The Physical Materials

Deposits are a direct function of available sedimentary material, so this section will examine those sources at the London Avenue Canal breach and the relationship between the source and the depositional sites.

The levee breach eventually widened to 61 m (200 ft), but the initial flow through the narrower outlet can be estimated from a house that was carried some distance. The current struck the southwest corner of the house, rotating it as it moved off its foundations. Another indication of the flow's power was seen by divers during levee repairs. They estimated that a scour pit had been excavated; Nelson and Leclair report the hole as being 6.1 m (20 ft) below sea level, or about 2.4 m (7.9 ft) below the original canal bottom. If the scour depth were actually below the canal floor, then it would account for some of the splay sediment and the high proportion of PIBS (Figure 4). That scour was less than that in other flooding (e.g., Vink, 1926), perhaps because of the shorter duration of the eroding current and the smaller flood basin.

Using the calculation of 6.1 m below sea level, Nelson and Leclair (2006) estimated the volume of the scour to be about 7,800 m^3, which accounts for only 29% of the 26,380 m^3 of sediment deposited in the immediate area. The rest of the sediment must have come from artificial levee fill (ALF), RSD, eroded topsoil, and other areas of the canal bottom. Sediment deposited on the neighborhood side of the breach included several different compositions (Figure 3) and formed several distinct layers (Figure 5).

At the breach, the PIBS deposits lay no more than 2 m (6.6 ft) below the original canal bottom (Nelson and Leclair, 2006), probably overlain by RSD (Figure 4). Nelson and Leclair described it as "a 1.5 m to 3 m thick layer of organic-rich clays that contains peat and wood fragments" (2006, p. 2). Above it, a layer of well-consolidated fine clay covered the canal bottom. This layer was peeled up in sheets and rolled into sand-to-pebble size clay balls that were then deposited as clasts in the splay sediments. The ALF constituted the other significant source of sediment from the canal (Figures 3 and 4) and was the major component of the lowest, largely–unsorted clastic Layer A (Figure 5), along with a significant volume of clay balls (Figure 6). Nelson and Leclair (2006, p. 2) reported: "The artificial levee fill consists mostly of clays with pockets of sand, silt, and occasional logs and shells."

Sedimentary deposits in the study area covered about 54,670 m^2 (Nelson and Leclair, 2006) in an irregular pattern determined largely by local obstructions. Total thickness varied from 1.8 m (5.9 ft) near the breach to < 0.3 m (1 ft) about 400 m (1,312 ft) away. This resulted in a reported slope on the sediment surface of about 0.004.

Sediment was entrained in the current in several distinct ways. One was by direct flow, but several indirect factors proved important. One was liquefaction of the PIBS. Water in the canal is normally at the same level as Lake Pontchartrain, 0.6 m (2 ft) above sea level. The storm surge at the canal was 1.9 m (6.2 ft), and so the maximum wave height in the canal would have been at 2.5 m (8.2 ft) above sea level (Figure 3) (Nelson and Leclair, 2006). The canal bottom, at -3.7 m (-12 ft) msl, would have been well above the storm wave base, forcing each storm surge to pump water into the PIBS (-5.7 m msl) like a huge piston. Hydrostatic pressure would have caused liquefaction, decreasing PIBS cohesion and shear strength. This weakness at the base of the levee's core of sheet piling, combined with the weight of the heavy concrete parapets atop the levee, forced the catastrophic structural failure.

At that point, a powerful current, which flowed into the neighborhood and began widening the breach, scoured the immediate area near the breach, and deposited sediment as the flow dispersed or was slowed by obstacles. During that time, more energy was added to the system by storm waves surging up the canal. Each one would further erode the scour pit, adding additional, corresponding pulses of sediment to the outflow. Flow was powered by a fall height of up to 4 m (13 ft), with a functional head pressure equal to the total mass of the top 2 m (6.6 ft) of water in Lake Pontchartrain. That was why the initial flow was sufficient to dislodge and move a house. Torn from its concrete foundation, it floated 36 m (118 ft) down current until it wedged against a large tree, rotating 137° clockwise due to the slightly off-center pressure (Nelson and Leclair, 2006). High current strength was also illustrated by the lack of sedimentation between the breach and the final resting site of the house, caused by high current velocities.

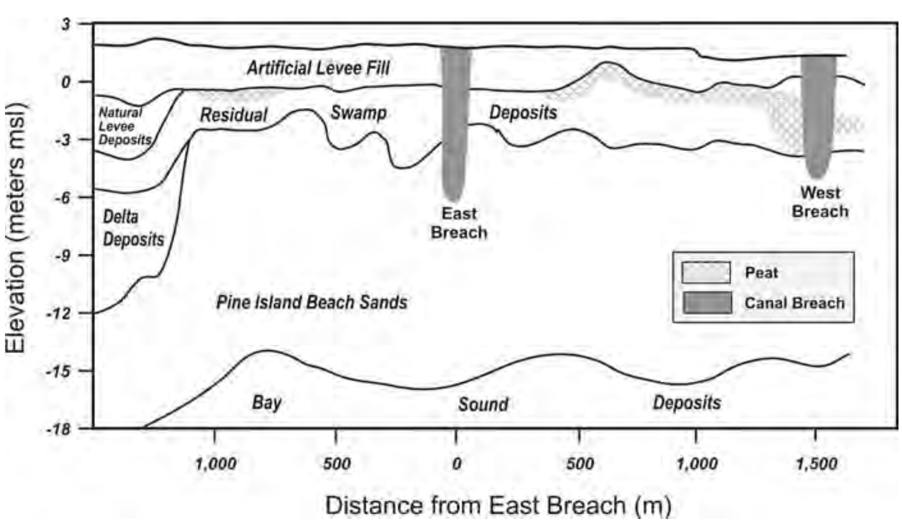
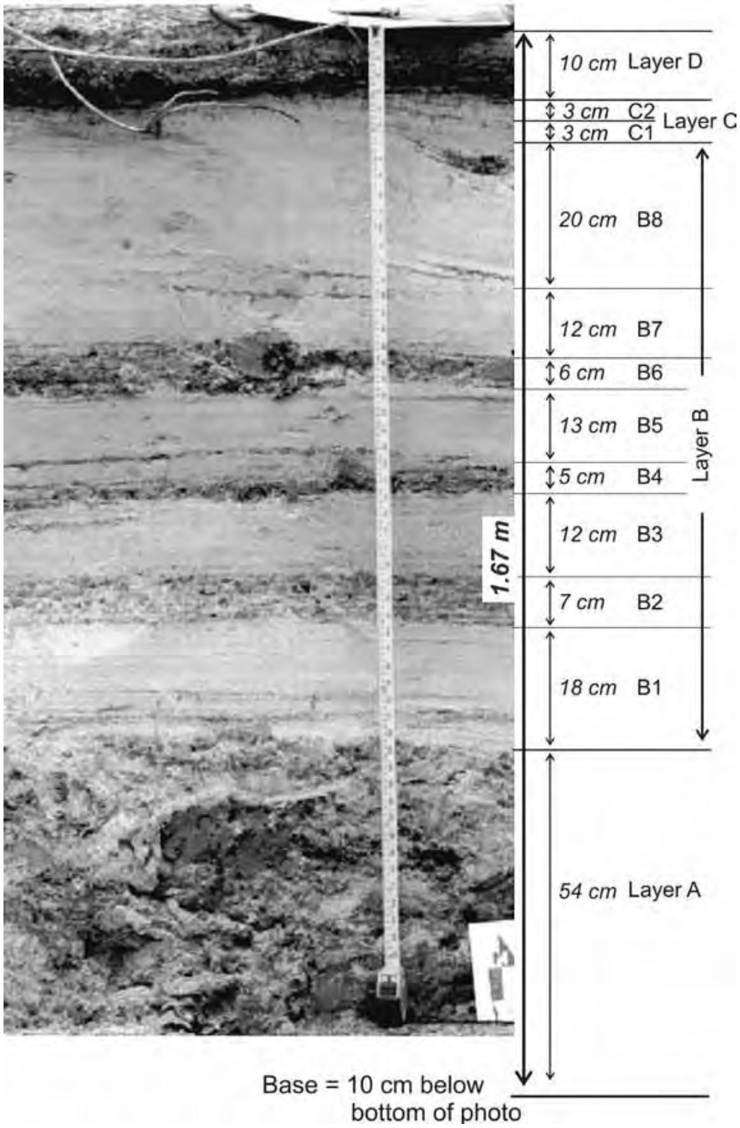


Figure 4. Cross section of major sedimentary deposits under the London Avenue Canal neighborhood from south to north. This study is of the east breach. After Nelson and Leclair (2006, figure 3).

Splay Sedimentation at the Breach

Flow through the breach resulted in the development of a splay deposit, with characteristics that indicate the mechanics of the water flow. Figure 5 and its accompanying diagrammatic version, Figure 6, show one of the thickest and most complete cross sections through the splay. Nelson and Leclair (2006, p. 3) concluded, "It is clear that the sand originated from the buried Pine Island beach deposits in the subsurface." However, there are both white and pink sand grains present in the splay. Because the PIBS is white (Figure 6), the pink sand, probably colored by oxidized iron or residual organic matter, probably comes from RSD, or possibly the PIBS was colored by a mixture of RSD. Layer A, the basal deposit (Figures 5 and 6), is assumed to be ALF. Ubiquitous clay balls are probably from the canal bottom clay; thus all four sediments in the area of the breach contributed to the splay sediments. Since the scour pit provided less than 30% of the total sediment, it is likely that similar material was carried up the canal (Nelson and Leclair, 2006). It is also possible that it was derived from the scour pit on the west side of the London Avenue Canal, just to the north. Thus, sediment (except for Layer D, discussed later) originated locally. Nelson and Leclair (2006, p. 3) determined, "The sand fraction in all parts of the splay deposits consisted of fine sand (0.125–0.25mm)."



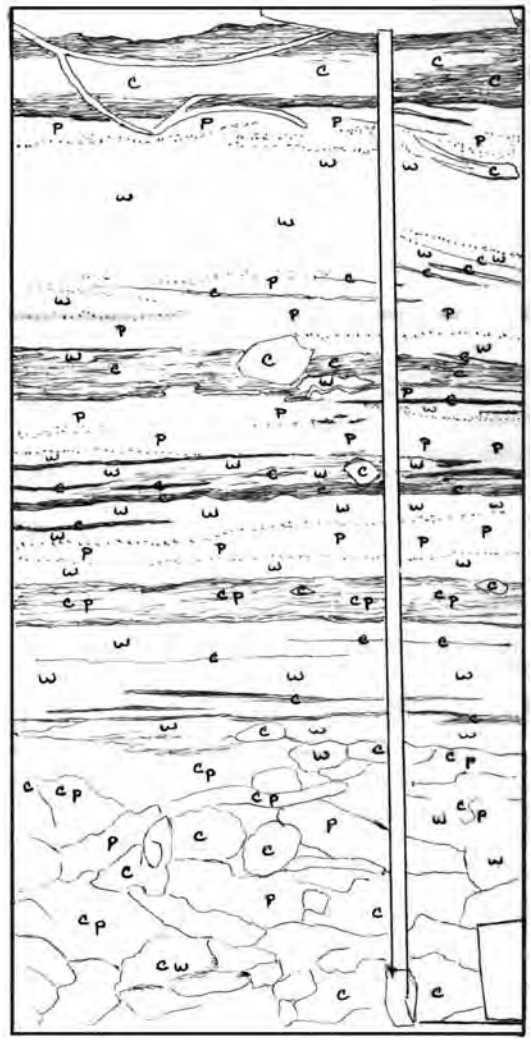


Figure 5 *(left)*. Vertical cross section through nearly the complete deposit at Point X, Figure 7, on west side of Warrington Drive. Bottom of Layer A is in standing water 10 cm below measured section shown, for a total of 1.63 m. Measurement of layers approximated from scale in photo. From Nelson and Leclair (2006, figure 6 with dimensions added).

Figure 6 *(right)*. Redrawing of Figure 5 showing the areas where primary composition is pink sand (P), white sand (W), and clay (C) in the cross section. From Nelson and Leclair (2006, their figure 6).

Assuming most of the sediment came from the immediate area, how was so much material entrained in such a limited distance? Would the rapid current alone provide the necessary force to suspend and transport this quantity of sediment? A particle at rest on the bottom of the canal would have experienced gravitational and frictional forces—both adhesive and cohesive—that would tend to keep the particle on the bottom. To move up into the current, it would have to experience equal or greater hydrodynamic lift forces. These forces can be produced by (1) irregularities in the flow and (2) irregularities in the particle. The part of a current that interacts with substrate particles is called the boundary layer. In shallow water it may extend to the surface. Below this layer, water moves between particles in the substrate in what is called the absorbed layer, where cohesive forces prevail. Between the boundary layer and the absorbed layer is the viscous sublayer, where viscous forces prevail (Nichols, 1999, p. 43).

Under normal flow conditions, turbulence is caused by irregularities in the sediment surface within the viscous sublayer. Rarely, turbulence may be caused by forces acting on the water/air interface and may extend as far as the absorbed layer. Turbulence produces upward flow, carrying particles up into the current. Particle lift also occurs by Bernoulli forces (McLane, 1995). However, Southard (1971) established that in laminar flow with low turbulence, Bernoulli forces alone will not cause an appreciable quantity of fine sand to enter the suspended load.

PIBS and RSD sediments at the canal bottom were protected by a layer of well-consolidated clay—the source of clay balls and drapes in the deposits. Hjulström's diagram (reproduced in Nichols, 1999) indicates that the erosion of consolidated clay requires velocities up to 3 m/s in water approximately 1 m deep. Calculations will show that the mean water velocity at the breach did not attain this rate under normal flow. McLane (1995, p. 58, brackets added) noted: "Grains smaller than this [1.0 mm] do not project very far into the flow; their movement is due mainly to viscosity of the flow and is largely independent of turbulence." So if neither Bernoulli forces nor turbulence were sufficient, what added enough energy to create hydrodynamic lift at the London Avenue Canal? I suggest that storm surge waves are the answer.

These waves generally have a long wavelength but travel rapidly. McLane (1995) suggested storm surge waves with a 20-second interval would possess wavelengths of 600 m (1,968 ft), moving at 30 m/s. Wave base for such a wave would be one half the wave length, or 300 m (984 ft). This is far deeper than the 6 m (20 ft) shown in Figure 3 at the depth of the canal. Thus, these waves would transfer significant energy directly down onto the canal bottom. The canal depth would cause the storm waves to react as shallow water waves (McLane, 1995), where water particles travel in ellipses, not circles. The vertical component of that motion would act as a hydraulic pump, pushing water into the substrate while the extended horizontal motion (from the wavelength) would peel up the protective layer of consolidated clay. Thixotropic conditions would overcome the cohesion of the underlying sand, allowing it to be easily entrained in the current. This is shown by the equation for the length (l_1) of the horizontal semi-major axis:

$$l_1 = a/kD \tag{1}$$

Where a = ½ the wave amplitude, $k = 2\varpi/L$ where L = wave length as determined by storm wave interval, and D = depth to bottom, the distance over which energy was dissipated.

The height (l_2) of the vertical semi-minor axis is:

$$l_2 = a\,(y+D)\,/\,D \tag{2}$$

Where $y = 0$ at the water's surface and $y = -D$ at the bottom, where "the ellipse degenerates into a horizontal line" (McLane, 1995, p. 70).

Since the precise timing of the canal storm waves was not measured, I will assume a 20 second surge, along with the reported wave height of 1.9 m (6.2 ft). When a given wave ellipse had a semi-minor axis of 0 against the bottom, they would have a semi-major axis of about 33.3 m (110 ft) or a horizontal length of 67 m (220 ft). With energy concentrated in the forward horizontal motion, the entire power of the 1.9 m surge crest would scour the clay surface, peeling back large flakes and sheets. The exposed thixotropic sand would then lift easily into the current.

There was still some vertical vector of wave motion. Given the bottom roughness, caused by the original breach and scour (constantly being enlarged), considerable turbulence would have resulted. Equation (2) shows that 1 m (3.3 ft) above the bottom, the ellipse would have had about 0.67 m (2.2 ft) of vertical motion. Yet head pressure from Lake Pontchartrain was sufficient to force unidirectional flow, limiting the amount and effective direction of turbulence so that significant stirring of the sediments could not occur. As a result, sedimentary units are distinct and deposited in the order they were entrained.

If Layer A (Figure 5) formed from the first blowout of ALF, then sublayer B1 likely represents additional mining of PIBS with an energy pulse that eroded canal bottom clay, producing the line of clay in the lower part of B1. Three couplets, sublayers B2 through B7, reflect three additional, distinct energy pulses in the current—probably surge waves and their attendant wave trains. If so, they would have first stripped the clay off the bottom, unmasking the PIBS and RSD sands, which were then quickly entrained. The B2/B3 couplet may have been interrupted by the B4/B5 surge, indicating backwards erosion from the original scour up the canal and acquiring the sediment for the next sequence—B6/B7.

Assuming the original canal bottom consisted of (1) canal bottom clay, (2) RSD, and (3) PIBS, in that vertical order, and based on the depth of the original scour, once the white PIBS from the scour was deposited in B1, erosion back up the canal channel would have removed the pink RSD, the primary sand in B3, B5, and B7 (Figure 6). This suggests that storm surge ellipses were *widening* the original scour rather than deepening it. Even in the top half of Layer A, the pink sand indicates RSD. This storm surge theory is supported by the regularity of these couplets, particularly the similar thickness of the sublayers.

If the underlying current was constant and regular (based on the large pressure head), the couplets suggest overlaying energy pulses. But if this accounts for B1 through B7, what was the origin of Layer A's distinct structure?

A possible answer is found in the nature of the breach. The sheet metal pilings that were the functional core of the levee failed catastrophically, resulting in a wall of mud and water surging through the breach. This most likely occurred in conjunction with a storm surge, 2.5 m (8.2 ft) above msl. With the protected land at -1.4 m (-4.6 ft) msl, that explosive wall of water would have been up to 3.9 m (12.8 ft) high, though it probably dropped to 2.5–3.0 m (8.2–9.8 ft) almost immediately. Even so, this is nearly the height of the local houses. Layer A was the result of this initial wave. The lack of sediments around the foundation of the displaced house and beyond (Figure 7) suggests that the current there was supercritical and moved through the area as a turbidity current, driven by the slope of the falling water and the head pressure. "Beyond the mouth of the channel [avulsion] the flow spreads and weakens, and the turbidity current eventually collapses and deposits its suspended load" (McLane, 1995, p. 79, brackets added). Layer A, composed of a wide variety of materials with clasts up to 20 cm (8 in) in diameter, formed when the turbidity current of the initial breach simply collapsed, depositing those sediments nearly instantaneously.

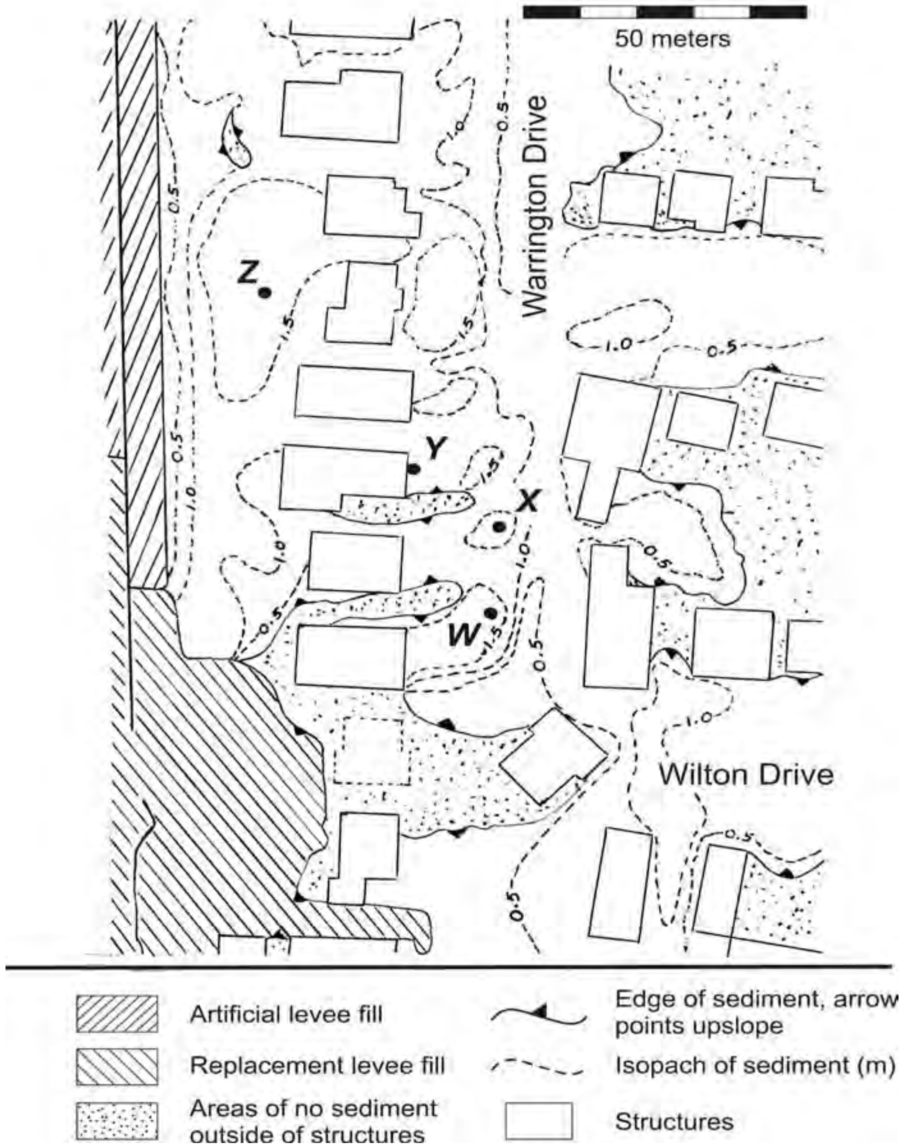


Figure 7. Map showing sediment depth distribution by isopachs in the immediate area of the levee breach. Points W, X, Y, and Z correspond to photos of sediment cross sections. After Nelson and Leclair (2006, figure 4).

Nichols (1999, p. 58, parentheses in original) had stated that "in the context of geological time, turbidites deposit 'instantaneously.' The time taken for the thin layer of suspended sediments to be deposited on the top of the turbidite is many orders of magnitude longer (months to hundreds of years)." That conclusion does not appear valid for the Katrina splay sequence. Instead, Layer A appears to have been "abundant particulate matter in suspension" in which "motion imparts turbulence" (McLane, 1995, p. 78). That situation was extremely short-lived; there is no segregation of clasts or graded bedding, and deposition appears to have been immediate, followed quickly by laminar deposition in more regular flow with superimposed storm surge waves. Layer D, the uppermost unit, is also distinct from the underlying laminar couplets. It contains no visible sand. It is largely clay but lacks the clay balls of lower layers. Nelson and Leclair (2006, their figure 7 caption) describe Layer D as follows: "Darker material consists mostly of a wide size range of clay pellets."

Using the location map (Figure 7), we can examine the details of the bedding at several points. At point W (Figure 8), Layer D is approximately 12 cm (4.8 in) thick, as measured just to the left of

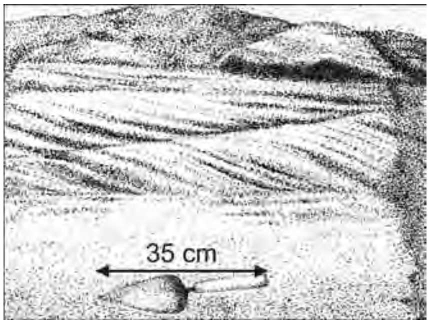


Figure 8. Vertical cross section parallel to flow at Point W showing lapping layers of cross bedding, sublayer B8, near the top of the section. Modified from Nelson and Leclair (2006, figure 7C).

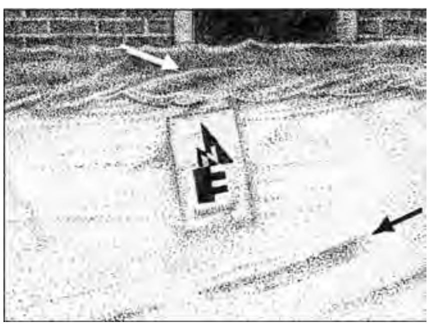


Figure 9. Vertical cross section at point Y on the front porch of house, showing ripples with clay coating (white arrow) and clay drapes in cross beds (black arrow). Modified from Nelson and Leclair (2006, figure 7D).

Sediment		Description	Origin
BRG	Breach Repair Gravel	dark granular clay and gravel which produced a dark clay dust fraction settling out of suspension in relatively quiet water	Unknown. Transported to site and dumped or pumped into place to repair levee breaches
ALF	Artificial Levee Fill	mixed appearance "clay with pockets of sand, silt, and occasional logs and shells"	Largely derived from RSD; used as fill on top of RSD ~100 years ago
CBC	Canal Bottom Clay	dark "gravel-size mud clasts > 500 mm in diameter to sand-sized pellets" with occasional large clasts up to 10 cm or more in diameter	Protective layer of clay that accumulated on canal bottoms over ~100 year history
RSD	Residual Swamp Deposits	dark "1.5-3-m-thick of organic-rich clays that contain peat and wood fragments"	Swamp sediments which once occupied land between river & lake prior to ~100 years ago
PIBS	Pine Island Beach Sand	mature white "fine-grained sand [0.125 - 0.25 mm], shells, and shell fragments"	"offshore currents produced a sand spit extending from what is now southwestern Mississippi toward the present day location of New Orleans"

Table I. Sediment sources for the Katrina splay deposits. All quotes from Nelson and Leclair (2006).

the high point at the top center of the photograph. Point X (Figure 5) shows Layer D at 10 cm (4 in). At Point Y (Figure 9), Layer D has thinned to less than 1 cm, just a dusting clinging to the surfaces of the top ripples. At Point Z (see Nelson and Leclair, 2006, figure 7B), Layer D is only a few cm thick. Thus, Layer D thins dramatically away from the breach. As the last sediment pulse, it appears that most of its sediment was carried as suspended load. The morphology of the dark sediment on the surface of the top ripples (Figure 9) suggests it was emplaced as water drained vertically down through underlying sand bodies, perhaps by settling after the flow equalized or during later pumping. In either case, it is characteristic of sediment deposited in the absence of a current, being thin and conforming to the surfaces of underlying bedforms. It thus suggests that the current had ended prior to its deposition. The only indication of a current velocity change is the ripples themselves superposed over the laminar layer. The only sediment that arrived after the current had stopped and would have dispersed from the force of being dumped into the water would be the breach repair gravels (BRG).

Repairs on the 17th Street Canal took place 4–7 days after the hurricane struck (Thursday, September 1 through Monday, September 5, 2005) (Timeline, 2006, pp. 8–9). They began by closing the lake end of the canal to cut off as much current as possible. Since this canal was on the western edge of the flooding (Figure 1), the breach was accessible by road on the non-flooded side of the canal. Breaches on both sides of the London Avenue Canal caused it to be surrounded by floodwater. There is no account of the repair procedure for this canal, so I can only assume it was much the same, either concurrently or immediately after the 17th Street Canal. Given the lack of access, the former would have required barges to transport the breach repair gravel (BRG).

Based on the dispersal of the settling fraction of the BRG in quiescent waters, the breadth of the bedforms suggests the BRG sediment was dry. Wet clays would have had more cohesion, producing less suspended load. Dumping or pumping BRG into standing water would cause both turbulence and a radiating current from the point of impact. Part of the sediment would go into suspension, moving outward as a turbidity current for a short distance before collapsing. This would account for the varying thickness from Points W to Y, where it essentially vanishes, showing the collapse occurred between points X and Y. The absence of a wider settling pattern is a good indication that no area-wide current was circulating during settling. With the recognition of the occurrence of BRG, the number of distinct sediments is five (Table I), accounting for all observed sediment (Figures 5, 8, and 9).

Energy in the Sediments

A characteristic of splay geometry is the rapid dispersal of flow over the fan-shaped delta. Was this seen at the Katrina splay deposits? The current was powerful at the breach. At 38 m (125 ft) away, the pressure was sufficient to tear a house from its foundations and transport it another 35 m. It would probably have gone farther, had it not lodged against a tree (Nelson and Leclair, 2006). Including rotation, its rear corner traveled 64 m (Figure 7). At Points W and X, 80 m (262 ft) and 104 m (341 ft) from the breach, respectively, the current retained sufficient strength to transport cars. Sand beneath them indicated that they were suspended in the current for at least a short time (Nelson and Leclair, 2006). Though no mention is made of the distance they moved, one photo (Nelson and Leclair's figure 5C) shows vehicle roofs regularly spaced, not stacked against a barrier. Thus, it is unlikely that the cars moved as far as the house. Nelson and Leclair (2006, p. 3) believed they "had been floating for some time." But given sufficient current to lift and transport cars, would it not have moved them farther? If not, how did the sand get beneath them?

Perhaps the answer is the timing of the events. If Layer A formed almost instantaneously, the cars would not have to have remained buoyant very long. The "layer of sand" under the cars likely represents the collapse of Layer A before it reached the moving house (Figure 7). Also, the current remained quite strong for some distance from the breach, as seen in the sediment distribution. A comparison of Nelson and Leclair's figure 5A, looking from Point Z back toward the levee breach to the rear of the house, and their figure 7B, showing the cross section at Point Z, compared with my Figure 5 reveals that bedforms remain quite similar, although Point Z is about 90 m (295 ft) from the breach, while Point W is only about 68 m (223 ft) away. Using these lines (breach to points) as radii, the circumference of the resulting semicircles would grow from 216 to 283 m (709–928 ft) when obstructions are taken into account, an increase of about 20% (Figure 10). Similarity in bedforms over this distance suggests that the total energy in the current was sufficient that the velocity did not decrease appreciably for some distance. When energy did drop, flow depth decreased so that the velocity was maintained and the bedform did not change. This is the expected relationship between kinetic energy (Froude number), flow velocity, and depth.

Another factor in the current behavior was the presence of obstacles (e.g., houses, cars, walls), which dramatically influenced sediment thickness. In the area around the dislocated house, ero-

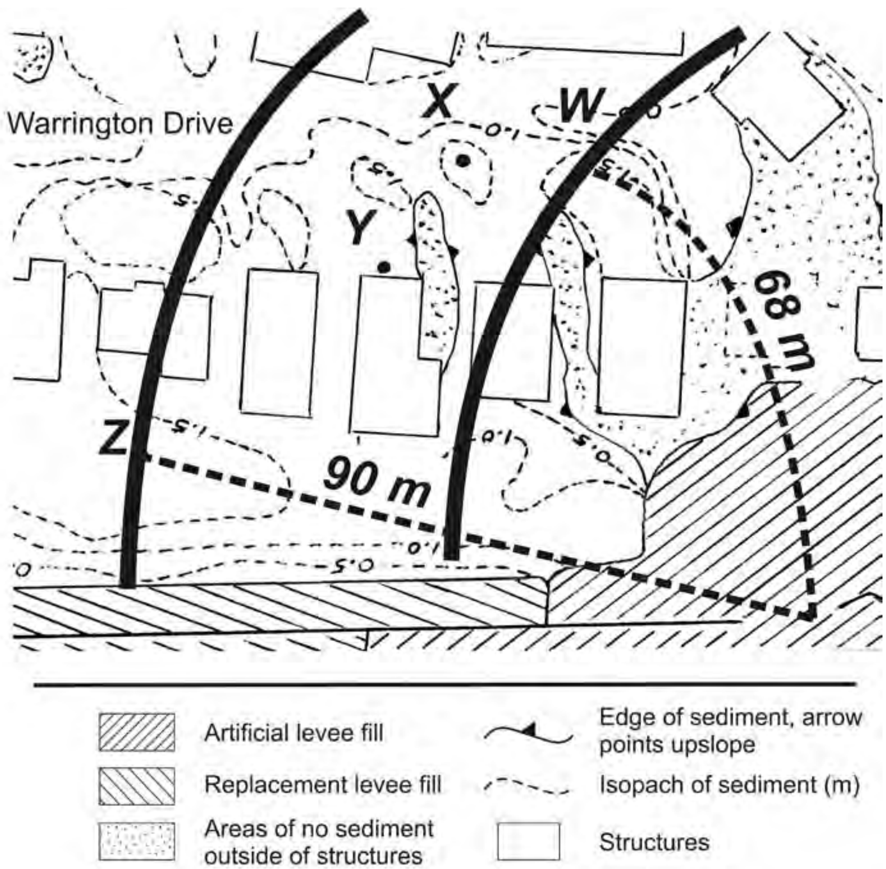


Figure 10. Distance of 68 m to W would produce a semicircular arc of 216 m, and to Z (90 m), an arc of 283 m, an increase in distance of 20% that flow energy is spread across.

sive zones formed between the levee wall and the first row of houses to the west, between the second and third houses. According to Nelson and Leclair (2006, p. 3), the obstructions "created high flow-velocity zones capable of transporting all available material." West of the first five houses (Figure 7), sediment thickness varies in a distinct pattern, though one not clear on the isopach map because the provided elevations are not at a fine enough scale to define the ridges visible in the photographs. Nelson and Leclair (2006, figure 5A) show two ridges parallel to the houses and levee; one ridge near the houses, the other near the levee. Between them is a thin zone. This depositional pattern is reflected in the laminar bedforms spread over the area, which were built roughly parallel to a continuously flat lower surface and rolling ridged surface on top (Nelson and Leclair, 2006, figure 7B). This depositional pattern suggests local variations in current velocity, with greater speed in the center of the temporary channel and along the levee, keeping material in suspension, but decreased energy toward the houses as shown by the ridges of sediment. This type of thickness variation also occurred along Wilton Drive (Nelson and Leclair, 2006, figure 5E), where sediment was preferentially deposited in a ridge along the north side of the street, the main channel in its center allowing less deposition.

Therefore, the major factors influencing sedimentation were: (1) energy dispersal as the current exited the breach, (2) formation of temporary high-energy channels, and (3) local obstacles. The area of highest energy was near the breach—an area that maintained supercritical flow—as shown by the zones barren of sediment (Figure 7). The first sedimentation occurred in the flow shadows between the levee and the houses and about 125 m (410 ft) downcurrent (Nelson and Leclair, 2006), as the flow expanded out into the open areas of the neighborhood. This was much closer than the 800 m (2,625 ft) at the 1993 SNY Island levee breach during the upper Mississippi Valley flood (Gomez et al., 1997), but both locations show deposition in a horseshoe-shaped rim, indicating the arc where flow transitions from supercritical to subcritical and allows sediment to be deposited. Those similarities suggest the same kind of focused power current. The SNY Island breach had a stronger head, leading to the larger eroded area in front of the breach.

Open flow paths, unlike those around obstructions, affected deposition. That was a function of the dependence of high-velocity laminar deposits on relative turbulence and sustained energy from the pressure head. Any time energy is dispersed, as in flow "leaking" perpendicular to the main current between the structures on Wilton Drive, sufficient carrying capacity dropped precipitously, and significant sedimentation did not continue past those points.

This suggests:

- Entraining a large amount of very fine sand and depositing it in a regular, rhythmically varied pattern requires a large, regular, rhythmical source of energy, a condition not typical to natural processes. In this case, that source was likely the storm surge waves.
- Constant bedforms over any distance produced by constant unidirectional flow require an adequate and constant source of energy (head pressure or slope).
- Patterns of sediment thickness indicate energy patterns in the flow. Obstructions were a primary source of these variations at the Katrina canal breaches.

Katrina Splay Deposits Versus Conventional Thinking

Traditionally, a crevasse is a break in a glacier or levee, and a splay is a sloping deposit of sediment deposited from that opening. These deposits resemble alluvial fans and are typically a part of river deltas. Splays are seen as relatively benign accumulations of sediments produced by infrequent, random sedimentary events. Nichols (1999) spent a full chapter describing crevasse splays on various types of deltas, and the expected sequence of strata in the facies. Despite an apparent order in the Katrina deposits, the facies approach seems remarkably inappropriate (Walker, 2007).

Since crevasse splays often occur on deltas, their sedimentary sequence is similar to an estuarine or deltaic setting. But Walker (2007) showed how facies interpretations could be misleading, when he noted how the virtually-instantaneous Katrina deposits mimic the expected sequence "of different environments over long periods of time," with which he produced a "hypothetical and erroneous depositional environment for the sedimentary section." He added: "It is apparent that the whole deposit of sand was laid down quickly… and the different characteristics observed in the vertical section represent changing flow conditions" (Walker, 2007, p. 9).

The Katrina splay deposits appear to have had quite a different origin from those of the standard delta scenario. There, the substrate would be a mud flat (Nichols, 1999). Occasional breaches would result in alternating layers of mud and sand, sand representing active sedimentation and mud, passive periods.

Geologists consider clay drapes to be another example of this alternating active/passive cycle. These features appear when clay settles on the lee slope of cross beds in a sandy deposit, like those in the Katrina splay (Figure 11, Figure 5, sublayer B8, and Layer C). Nichols (1999, pp. 138–139, brackets added) considers clay drapes to be an indication of:

> high or low tides when the current is changing directions, there is a short period when there is no flow. Whilst the water is still, some of the suspended load [clay] may be deposited.

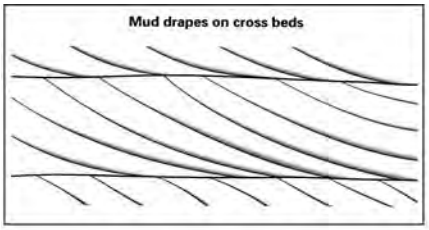


Figure 11. Clay drapes after Nichols (1999, his figure 11.6). Note regular pattern of clay layer on top and lee slopes of cross-bedded sandstone.

> When the current becomes stronger during the next tide the suspension deposit may not be removed because of the cohesive nature of the clay rich sediments.

When clay drapes cover a large flat area, like sublayers B1, B3, and B5, they are ascribed to tidal point bar deposition, where "the episodic nature of tidal flow allows fine materials to come out of a suspension on the gently sloping bar surface. Alternations of sand and mud on bar deposits produce a pattern of bedding referred to as *inclined heterolithic stratification*" (Thomas et al., 1987, cited in Nichols, 1999, p. 164, emphasis in original). In both cases, geologists assume that clay represents quiescent flow between periods of active sedimentation. Do the Katrina clay drapes support this idea?

Both drapes and inclined heterolithic stratification are found in the Katrina splay deposits. Figure 5 shows clay drapes on the lee slopes of B8, while B2, B4, and B6 would readily be interpreted as "inclined heterolithic stratification." Though they look like tidal reworking, the actual sequence of events contradicts that theory, and Nelson and Leclair (2006) cannot support their suggestion of reworking with evidence. The nature of the current flowing from the breach suggests otherwise; there were no redeposited sediments in barren areas, suggesting little to no reworking or resuspension of sediment. Furthermore, the sedimentary episode occurred so quickly (maximum 46 minutes) that there was not time for the classic active/passive cycle.

Clay drapes (Figure 11) also suggest the prevalent theory is wrong. It is well established by flume studies that when migrating dunes formed by high-velocity currents produce upper-regime bedforms, that a velocity decrease causes an abrupt change from dunes to ripples. Figure 9 shows a thin layer of clay adhering to ripple surface. If this were from the BRG, it would be a true clay drape settling from quiet water.

Other bedform changes can occur without a significant change in velocity. Laminar flat beds can grow into dunes in some cases with a significant increase in depth. Although ripples, dunes, and antidunes can collapse into laminar layers when velocity decreases below that needed to support flow separation, it appears that none of Katrina's sublayers exhibit characteristics of this phenomenon. Nichols (1999) gives no hint of a transition through collapsing bedforms to clay drapes, nor does his one lithified field example support it (his figure 11.7).

Likewise, Katrina splay sediments (Figure 5) show no transition through collapsed bedforms to clay drapes in their sequence of laminar sand and clay beds. In B6, laminar flat beds precede and follow the clay layer, indicating continued high flow. Also, B2 and B4 reveal laminar flat beds intermixed with the clay layer. B8 shows the same thing; both near the bottom and top, cross bedding precedes, follows, and is mixed with clay drapes. If the splay deposits do not represent successive facies (Nichols, 1999), as suggested by Walker (2007), then Layers A through C (Figure 5) were all laid down in one unidirectional current of relatively constant flow (from the excessive head), interrupted by regular storm surge wave pulses. The clay in the splay is in contrast to the pre-Katrina canal bottom clay, which accumulated slowly over many decades. But the sequence of strata beneath the canal are dissimilar from the splay deposits that show clay interspersed with sand, all in bedforms consistent with the observed high-energy flow through the breach.

Thus, Layer A is not a prodelta mud that McLane (1995, p. 201) suggested underlies the typical crevasse splay, where "much of the mud is deposited out of suspension." Even though mostly clay by composition, it fits better with the research of Schieber et. al. (2007), who demonstrated through flume experiments that clay and mud can be deposited in currents, not requiring low-energy conditions. Another argument for continual high-energy deposition is found in the presence of clay balls throughout the sequence—at least three exceeding 10 cm in Layer A, and another of similar size in B6. Even though most of the clay balls are smaller than a cm (Nelson and Leclair, 2006), some in the sand size range and others as flakes or floccules, none were deposited in quiescent conditions.

Clay drapes are common in the cross bedding of B8 (Figure 5), visible as gray shadows between the bedding planes. In Figure 8, the cross bedding is obvious, but many of the foresets appear to have a gray shadow under them due to an irregular surface. These gray areas are not merely shadows but are ubiquitous clay drapes.

Figures 8 and 9 show clay drapes as a common part of the bedforms. This suggests that the clay was deposited at velocities and depths similar to the sand, as was seen by Schieber et al. (2007). This is not surprising as they reported that the floccules under the scanning electron microscope revealed "a 'bumpy' surface pattern of closely packed ovoid bodies (0.2–0.6 mm in size)" (Schieber et al., 2007, p. 1761). That irregular surface resulted from the random aggregation of 1–5 µm clay particles. This tendency for clay to form ovoid bodies similar in size to fine sand suggests that both clay and sand would act similarly in deposition. A close study of the clay cross beds (Figures 5 and 8) shows two differences between foresets created by sand and those by clay. Most clay foresets do not reach the top of the dunes, and most of them fatten as they reach the tangential point at the bottom of the lee slopes. Again, these differences show that although both sediments were laid down at the same velocity, the clay ovoids responded slightly differently to flow separation—possibly due to a small difference in specific gravity or to the rougher surface of the clay balls, making them more mobile than sand. That would explain why they were swept off the dune crests and cascaded farther down the lee slopes. Another possibility is that clay ovoids may have a lower angle of repose.

But clay drapes in B8 were deposited just as rapidly as the sand. There were no active/passive cycles in the current velocity happening rapidly enough to account for all of the alternations in B2, B4, and B6. But the purity and thickness of some clay drapes suggest the very rapid formation of "floccule streamers," which can occur at a velocity over 0.8 m/s and a density of about 5% solids. Schieber et al. (2007) showed the slow formation of these streamers at 0.5 m/s and 0.0003% to 0.2% solids. Floccule streamers are large aggregates of floccules that form spontaneously by cohesive forces in suspension. Each streamer may settle out as a single unit or combine to form larger clay drapes. Unfortunately, Schieber et al. (2007) gave no information for higher solids concentrations, and I can only cautiously speculate based on the evidence from the available photographs.

Though the clay drapes appear significantly darker than the sand cross beds, they may not be pure clay. Schieber et al. (2007) suggest a shrinkage rate of 85% for pure clays. In working with ceramic clay, where a significant amount of sand or other filler has already been added to the clay to control the shrinkage, a

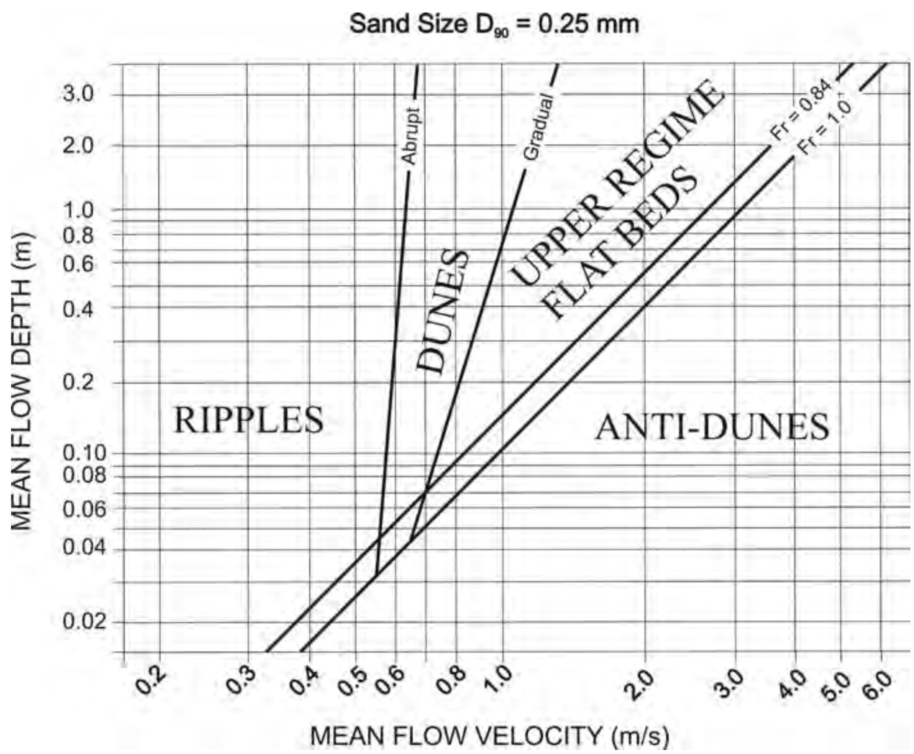


Figure 12. Logarithmic depth velocity diagram for 0.25 mm sand, showing transition lines between stable bedforms. After McLane (1995, figure 5.14).

clay vessel may still shrink 10–20% in the drying process prior to firing. The pictures give no indication of this high shrinkage in the clay bedforms, suggesting the floccule streamers collected a significant fraction of sand that made them more stable.

Examining the transition from flat beds to cross beds, B7 to B8, we see more evidence for constant flow. Cross beds start small, as seen prominently in Figures 5 and 8, and the change in bedform can be attributed to changing water depth, not velocity (Figure 12). Clay torn from the canal bottom represents continuing storm surges. Thus the clay shows that no decrease in velocity was taking place. The passing of each wave would raise the water level in the canal and propagate out into the neighborhood with little drop in depth or dispersal of energy, even after depth in the neighborhood reached the mean canal elevation. Perhaps it was near this time that the additional portion of the steel sheeting failed. Figure 6 shows some secondary opening of the breach after the initial failure (Figure 13).

Whatever the mechanism causing the change, the added water depth was sudden, and the resulting sedimentary bedforms accreted to their maximum height. The change from flat beds to cross beds could have resulted from an abrupt flow depth increase such as at 0.85 m/s in Figure 12, where at 0.2 m (6 in) deep, the bedform would be flat beds and would continue as such up to 0.5–0.6 m (1.6–2 ft) deep. When depth reached 0.8–1.0 m (2.6–3.3 ft), flow separation could have taken place and dunes would have started to form.

In Figure 8, the tangential contacts at both the top and bottom of the lee slopes of the dunes are visible. Since the top of the dune still displays the

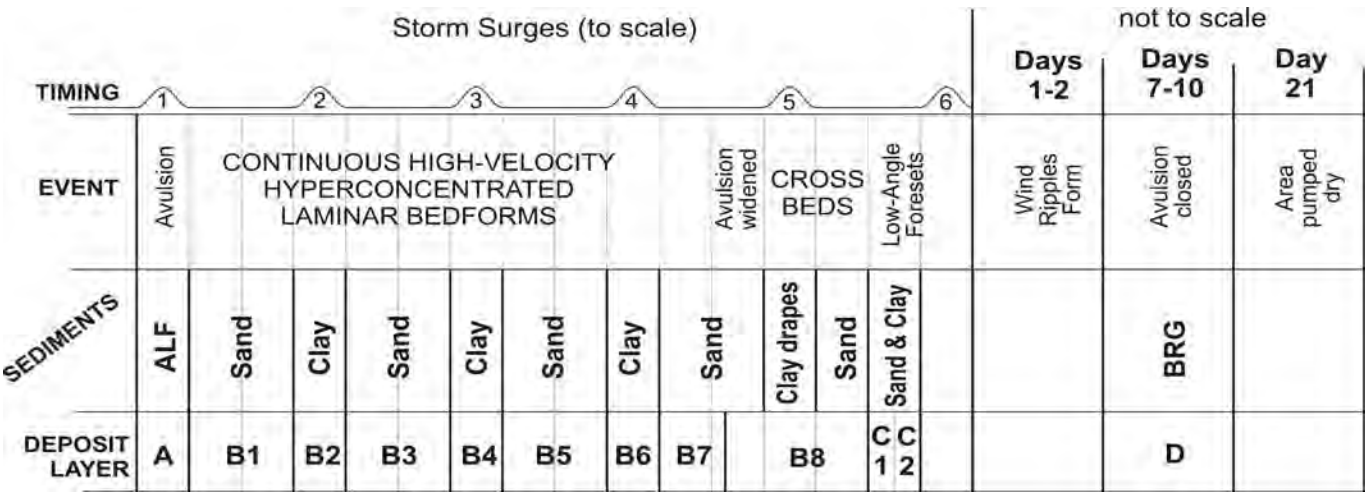


Figure 13. Timeline of significant events during splay deposit and development. Dotted lines under "storm surges" represent 7–10 second intervals. "Avulsion" may have required one full storm surge to develop. This timeline only documents the arrival and deposition of the sedimentary layers, from ALF (artificial levee fill) to BRG (breach repair gravel).

tangential transition from the stoss side of the dune over the crest and onto the lee slope, it is clear that the stoss side experienced little or no erosion. The diagonal line rising from left to right was a relatively stable stoss slope growing in elevation as the lee slope moved forward by settling sand from the suspension fraction in the separation zone with little or no contribution of the bed load fraction from the stoss slope.

Another indication of rapid deposition is the absence of evidence for erosion within the layers. This is shown by the tangential contact at the bottom of the lee slope, which indicates no erosion into the lowermost flat beds or the developing cross beds when the upper layer was forming and reaching the pinch out spot toward the upper right-hand edge of Figure 8. Eventually the cross-bedded layers of B8 were overlaid by Layer C1, which in both Figures 5 and 8 appears as a very low angle foreset. It appears that the relative depth dropped again. This is reasonable since the depth line of Figure 12 slides down past the transition line for upper-regime flat beds. The slight slope to the beds in Layer C suggests the depth remained in that transition zone. Such flat beds will deposit laminar layers on slopes up to the angle of repose (30°-40° for sand) (Berthault, 2002), and distinguishing between low-angle cross beds and angled high-velocity flat beds is difficult. At any rate, these cross beds were not formed by the typical advance of dunes. Instead, they grew as tilted high-velocity flat beds on an inclined plane in the separation zone of the lee slope, limited in height by water depth.

Given what we know about the breach, it is likely that after the catastrophic deposition of Layer A (Figure 5), the current remained essentially constant, with minor depth fluctuations through deposition of Layer C. Although clay drapes are more prominent in B8, they are clearly present as early as B1 and found in the intervening sublayers. Clay concentrated in B2, B4, and B6 is an artifact of the hydrodynamics of the continuous high-flow conditions, not decreases in velocity.

Abundant clay drapes in B8 suggests a fifth energy pulse that entrained a significant amount of clay. The higher proportion of clay at Point W (Figure 8), closest to the breach, and the lower amount at Point X (Figure 5), and the near absence of clay at Point Z may be connected to the decreasing carrying capacity of the flow for floccule streamers as the current dispersed.

An anomalous example of clay drapes is found at Point Y (Figure 9). The direction of slope appears reversed. But this was caused by local variations in the current in a partially enclosed porch. (Note: the angle of the mud drapes compared to the ripple crest shows that the cut surface was not parallel to current flow.) Another clay drape is at Point Z, adjacent to the top of the trowel handle visible in Nelson and Leclair's (2006) figure 7B. The cross section is perpendicular to flow, and the dark, discontinuous lines in the left half of the figure are clay drapes seen head on.

Overall, the sequence, from Layer A through C, appears to be a continuous deposit marked by 5–6 energy pulses. If these pulses occurred as rapidly as every 20–30 seconds, then this entire sequence was deposited in 2–3 minutes. However, this time frame for deposition does not imply that the entire neighborhood basin was filled with water in that same time span. Deposition took place under a relatively shallow flow of water that projected upwards above the fringe of the deposit no more, and probably significantly less, than it had near the evulsion where deposition began. For the water level to reach maximum elevation across the entire neighborhood basin may well have required closer to the 46 minutes reported for flooding the Lower Ninth Ward. The limited extent of deposition (about 400 m) indicates the limit of sediment transport by the hyperconcentrated flow.

Once more, the lack of significant sediments in the areas of supercritical flow during the original period of peak deposition suggests wave propagation continued with the same energy needed to maintain supercritical flow in those areas until the sediment load had diminished. The full height of two 3-cm sublayers in C indicates that nothing is missing. Erosion or reworking of the already-deposited sediment in this continuing flow did not occur, but the current did continue for some period of time afterwards.

This is supported by escape holes cut through the roofs of local houses—there was no other means of escape, even minutes into the flooding event. Once the water began to flow into the neighborhood, it continued until it quickly reached its maximum of 1.9–2.4 m (6.2–7.9 ft).

This leads to the following conclusions:

- A continuous sequence of sediments requires a continuous current; velocity changes will be reflected by bedform changes. Absent this, no velocity shift appears evident.
- Naturally occurring, low-velocity currents, such as tides, do not provide an adequate model for catastrophic events.
- The Katrina bedforms appear continuous, including the clay drapes, absent evidence of current variations. Repetitive cycles are accounted for within the context of constant, unidirectional flow by energy pulses from storm surge waves.
- If these waves had intervals of 20–30 seconds, and six or less are seen in the recurring cycles, then the entire sequence, 1.6–1.8 m (5.2–5.9 ft), was deposited in 2–3 minutes, a rate of 0.6–0.9 m/minute.

Bedforms

Nelson and Leclair (2006, p. 3) described the Katrina splay bedforms as:

> overlying a massive clayey-sand layer… planar strata were dominant and continuous…. Low-angle strata… reflected the shape of the ridges surfaces…. Medium-scale cross-strata overlay planar strata only along Warrington Drive…and small-scale cross-strata were largely absent, except in protected areas, such as houses, porches…. Spectacular cases of climbing dunes were seen on obstacles, such as cars…. Cross-stratification around obstacles indicates different flow directions.”

Later they note that the “planar strata…indicates that an upper-stage plane bed, and hence, an upper flow regime, prevailed during much of the deposition” (Nelson and Leclair, 2006, p. 3). The difference between these deposits and “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” (Bridges, 2003).

This agrees with the well-defined, cm-scale planar strata in Figure 5, but not as well with the structure of the mm-scale layers. While B1-B7 show a regular pattern of flat, alternating beds of sand and clay, continuous parallel to flow, the sand and clay laminae in the mm-scale beds are unusually discontinuous. Curiously, planar strata perpendicular to flow are also discontinuous. The laminae are patches or smears of one type of sediment overlapping other patches or smears of other types. They combine to form an irregular but flat stratal unit—much like small blankets spread out into a random pile with their long axes arranged parallel.

We cannot understand the planar strata without an explanation for this arrangement. “Planar strata” is a descriptive term used for a variety of bedforms common in the rock record, which, when lithified, form relatively flat bedding surfaces. They are often mined for flagstones for paving and building (McLane, 1995). There are three specific sets of flow and sediment conditions under which flat beds form. Each of these is specific enough to be differentiated by keen observation. These include: (1) low-regime flat beds, (2) upper-regime flat beds, and (3) antidunes (Figure 14). Confusing these will drastically confuse interpretation of flat beds found in the rock record.

Lower-regime flat beds occur only in medium to coarse sand, > 0.7 mm (Nichols, 1999). Grains protrude above the viscous sublayer, generally no more than 0.6 mm thick. In that layer, friction exceeds turbulence, and streamlines are smooth. In a large channel, the bottom is the only surface to produce turbulence, which originates at the upper boundary of the viscous sublayer and moves up into the current. Grains exceeding its thickness create turbulence and will eventually cause flow separation. Moving bed load during sediment accretion create perturbations that cause additional grains to accrete and non-laminar bedforms to grow.

As sands finer than 0.6 mm accrete, the viscous sublayer moves up with the new channel bottom, and flow separation will occur above the location of a perturbation. This causes the formation of individual ripples and a rippled bedform. In medium to coarse sand, continuous flow separation cannot take place (Nichols, 1999). When accretion begins at a perturbation, a ripple will start to form at the first incipient flux

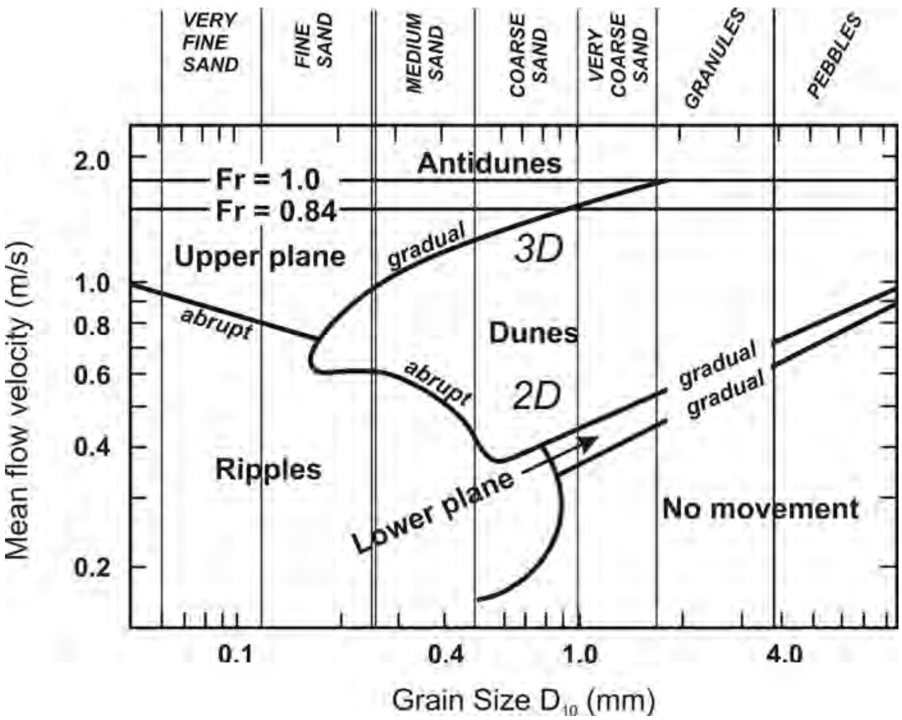


Figure 14. Bedform stability field by grain size classifications showing the bedform progression, up and down, for velocity increases and decreases. From McLane (1995, figure 5.15).

of flow separation, but then turbulence will overwhelm and capture the motion and the incipient ripple with collapse (McLane, 1995). This constant washout of the ripples bedform produces relatively flat beds with an irregular, wavy internal structure (Barwis and Hayes, 1985). This results in lower-regime flat beds not having a continuous, flat laminar internal structure and being poorly defined at their parting surfaces (Nichols, 1999). By contrast, there is much better definition in flat beds originating in a high-flow regime due to the presence of primary current laminations of low-form elongate ridges and furrows parallel to current direction (Nichols, 1999).

As the sweeping high-shear turbulence parallel to flow is transferred down into the viscous sublayer, the resulting drag of the lowest streamline may not be strong enough to lift individual grains of sediment, but it does pull more mobile fluid particles up from the intergranular spaces, and this fluid is replaced by fluid pulled down into the viscous sublayer, producing Taylor-Gortler vortices (McLane, 1995) that produce the striations of the parting laminations.

Distinct parting surfaces also form in high-regime flat beds due to separation between bed load and suspended particles. Julien et al. (1994) document the extensive speculation about the causes of parting surfaces. McLane (1995, p. 84) even went so far as to speculate, "Bedding planes take more time to make than the beds themselves." This is contrary to Julien et al. (1994), who demonstrated that both bed and parting surfaces form simultaneously, and at the same rate, although at different locations. This provides separate laminae of the larger particles, which are rolled or saltated into position, while suspended fines, which have a constant fall velocity even in fast currents, land on top of the laminae of heavier particles. It is the fine sand surface that varies shrinkage, due to a greater grain surface-to-volume ratio with weaker intergranular adhesion. This results in parting surfaces.

Third, flat beds are formed from antidunes. Often associated with visible small surface waves forming directly above the dune front, antidunes are also referred to as inline waves. They grow either upcurrent or downcurrent by depositing sediments on either the stoss or lee slope of the dunes. Occurring at a minimum Froude number of 0.844 to 1.0 (Kennedy, 1963), antidunes form within the range of supercritical flow. This flow fosters turbulent breaking waves on the surface. As the antidunes grow taller, the inline wave's crest rises until it breaks. When the inline wave breaks, turbulence is directed downward, and the dune front collapses into a flat bed (McLane, 1995). This produces the same irregular, wavy internal structure as the washed-out ripples that form lower-regime flat beds (see figure 7; Barwis and Hayes, 1985).

Which of these three flow conditions produced the Katrina splay deposits? The mm-thick layers do not show the washed-out internal structure typical of low-velocity flat beds or antidunes. But, neither do they show the obvious lamination expected of upper-regime flat beds. Instead, they exhibit anomalously discontinuous laminae. Also, the only ripples are those found in the uppermost layers (Figure 9), and since lower-flow flat beds form at velocities too low to produce ripples, they are likely not the "planar strata" of that flow regime. And, although the flow reached supercritical status regularly, Point X (Figure 5) shows supercritical flow only at the initial levee break and shortly afterwards. A careful study of B1 (Figure 5) does not show any more reverse-sloped cross bedding here than in other sublayers, making an antidunes origin unlikely. Therefore, I conclude that the "planar strata" are upper-regime flat beds based on the mathematical calculations.

τ_*	S	d_{50} (m)	d_{max} (m)	density	% solid	τ_0 (N/m²)	h (m)	Manning			Logarithmic		
								n	V (m/s)	Fr	k	V (m/s)	Fr
0.055	0.00375	0.00025	0.03	2.00 g/cm³	0.05	15.41	0.40	0.016	2.13	1.08	0.0017	2.41	1.21
					0.09	14.76	0.37		2.03	1.06		2.30	1.21
					0.20	12.48	0.29		1.72	1.02		1.97	1.16
					0.30	11.35	0.24		1.52	0.99		1.75	1.14
				2.25 g/cm³	0.05	19.25	0.49		2.45	1.12		2.73	1.25
					0.09	18.44	0.45		2.31	1.10		2.60	1.24
					0.20	16.21	0.35		1.95	1.05		2.21	1.19
					0.30	14.19	0.28		1.68	1.01		1.92	1.16

Table II. Calculations of flow depth (h) and velocity (V) using both Manning and logarithmic equations showing the Froude number for each combination.

For these hydrodynamic calculations, the following symbols will be used:

γ_s = specific gravity of the solid phase

γ_m = specific gravity of the water/solid mixture based on the percent concentration of solids

d = diameter of the sediment particles

τ_* = dimensionless shear stress for the solid particles

τ_o = critical shear stress for initiating particle motion

h = flow depth

$\overline{V}$ = depth averaged velocity

S = slope steepness factor

g = gravitational attraction

The critical shear stress (τ_o) can be determined using the Shields parameter equation (Julien, 1998, p. 5):

$$\tau_o = \tau_* (\gamma_s - \gamma_m)\, d_{max} \qquad (3)$$

A density of 2.65 g/cm³ is used for the fine sand and 2.0–2.25 g/cm³ for the 1.0 cm (0.01 m) clay balls. Though the nature of the clay balls suggests a lower density, they were transported and deposited directly with the sand. This is consistent with the work of Schieber et al. (2007), examining clay flocculation in currents. The Katrina clay balls were both wet and consolidated, so these densities may be close. Since channel-bottom clay erosion was likely caused by energy pulses from storm surge waves, small deviations in density may have negligible effects on calculations.

Lalomov (2007), citing Polyakov (2002), places the boundary between Newtonian and non-Newtonian flow at 9% sediment load, while Julien (1998) gave a range of 5–60% for hyperconcentrated flows. Lowe (1982) places hyperconcentrated flow at 20–30%. Table II provides parallel results for 5%, 9%, 20%, and 30% solids by volume.

The τ_* values given by Julien (1998) for medium sand (> 0.25 mm) is 0.048; for fine sand (> 0.125 mm) the value jumps to 0.072. A mean value of 0.06 is sometimes recommended (Julien, 1998), but not knowing the sorting of grain sizes within the spread and realizing the sediments moved to dunes, which would have happened in 0.125 mm, I chose to use a value of τ_* = 0055 for Table II skewed toward the 0.25 mm grain size.

There is a 7 x 9 cm (2.8 x 3.5 in) clay ball in B6 (Figure 5). It appears to be the largest clast moved following the original breach. But, careful inspection shows that the layers of B6 are actually deflected downwards by the clast; it is likely an outsized clast that fell onto the flow and was rafted on top of the dense sediment layer. This also seems to be the case with the 3 x 5 cm (1.2 x 2 in) rectangular clast embedded in B4 just to the left of the tape measure. The largest clast entrained in the flow is the irregular 3 x 5 cm clay lump in B6 next to the right edge of the picture. The intermediate measurement for the lump, 3 cm is used for d_{max}.

The DuBoys equation (Lalomov, 2007) calculates flow depth (h) from critical shear stress:

$$h = \tau_o / \gamma_m S \qquad (4)$$

Nelson and Leclair (2006) propose a slope of about 0.004, but the use of their measurements returns S = 0.00375. This produces flow depths of 0.24–0.40 m. This depth is relatively shallow. A depth of 0.24 m (10 in) on the lower end hardly seems a threat to human life, but the escape holes cut into the roofs indicate such a threat existed. This further supports the rapidity of flooding—46 minutes maximum in the Lower Ninth Ward and only 2–3 minutes for the passage of 5 to 6 storm surge waves.

Using the Manning equation for velocity (Julien, 1998):

$$\overline{V} = S^{1/2}\, h^{2/3}\, n^{-1} \qquad (5)$$

Julien (1998) gives the value of the Manning coefficient (n) for fine sand (colloidal) to fine gravel as 0.02. The constant slope of 0.00375 is used for S since Schumm and Khan (1972) noted a strong correlation between sediment load, flow velocity, and slope; slope remained consistent relative to these other parameters in equilibrium conditions. The calculated flow velocity is then between 1.17 m/s and 1.91 m/s.

As a check on the Manning velocities, the logarithmic equation (Julien, 1998) was used:

$$\overline{V} = 5.75\, (g\, h\, S)^{1/2} \times \log (12.2\, h / k_s) \qquad (6)$$

As dunes are produced in Figure 5, Layer B8, this is a strong indication that the grain size was skewed more towards the upper end of the grain size range, so $k_s = 5.2\ d_{65}$ with $d_{65} = 0.00025$m.

All velocities obtained from the logarithmic equation produce Froude numbers that exceed unity, showing that they are too high. A $k_s = 6.8\ d_{50}$ was attempted without significantly better results.

Examining the Froude numbers for the Manning velocities and considering how many parameters had to be estimated, the most likely conditions seem to revolve around a density for the wet clay of 2.00 g/cm^3 and a range of 20–30% solids. This would confirm that the flow reached hyperconcentrated conditions as defined by Lowe (1982).

We need to understand the deposited thickness laid down by a single energy surge or wave. Were they individual mm thick laminae or thicker sets? McKee et al. (1967) noted the discontinuous nature of the unique beds of the Bijou Creek Flood, mixed with more common sand layers extending the width of the deposits. The latter indicated a current across the breadth of the flood, while the narrow, discontinuous layer demonstrated different flow conditions. He cited sets of laminae "three to four inches thick" that were "bent downward into shallow V's in three places [within one investigative trench]; the nearly horizontal laminae above and below were undisturbed" (McKee at al., 1967, p. 836, brackets added). They concluded that projectile pebbles—possibly launched out of the water—produced the impressions in the existing beds before being buried by more fine sediment. Because the pebbles landed on top of a stack of laminae and left a dented impression in the total stack, but not into the underlying laminae, all layers in the dented stack would have been in approximately the same stage of dewatering while the stack below had already compacted, and therefore, it was too dense to take on the indent. This indicates the laminae were laid down not singularly but in sets.

A second bedform McKee et al. (1967) document from the Bijou Creek Flood that seems to have a bearing on the concept of sets of laminae is convoluted structures. Convoluted bedding seems to be a terminal low-velocity bedform produced when high-velocity currents are suddenly slowed and "sediment was in the condition of quicksand" (McKee et al., 1967, p. 840). As cohesive forces were forming laminae at high velocities, the system experienced a sudden decrease in velocity and was unable to keep the laminae flat. The system pancaked like a high-velocity train suddenly stopping. The convoluted bedding shown in their figures 7 and 9 are sections of tightly convoluted ribbon and broken U-shaped structures, all formed from a set of laminae that appears to have been 7–10 cm (3–4 in) thick in its original flat form. Though no convoluted bedding is present in the Katrina splay deposits, these sets of laminae seem to be the basic structural unit characteristic of hyperconcentrated flow. This suggests that under hyperconcentrated conditions in a high-velocity regime, individual laminae (< 1 cm) are not laid down singly, but instead a multi-cm-thick set is laid down simultaneously. I believe that the 7–10 cm set of laminae documented by McKee in these two instances, constitute a single set separated from those above and below by a very short but significant period of time.

The occurrence of laminae in sets is analogous to Katrina's sublayers B2, B4, and B6—which are 7 cm, 5 cm, and 6 cm, respectively, or a mean of 6 cm. Is this the thickness of the storm surge sets? An examination of the 7 x 9 cm clast in B6 shows that only the lower half of the clay layer is deflected by the clast and the other half of the layer went around it. Because waves occur in a train, with the largest at regularly spaced intervals, B1, B3, B5, and B7, which are primarily sand, represent the train of smaller resonating waves between the storm surges, each leaving a set averaging 3 cm thick.

Rubin and McCulloch (1980, p. 222, emphasis in original) suggested: "The mean height of relatively straight crested sand waves in a train is generally *less than or equal to* approximately 1/6 of the mean flow depth." This 6:1 ratio may apply to other bedforms. Allen (1976) proposed that bedforms never exceed a 6:1 to 8:1 ratio of flow depth to bedform height. If a 3 cm-thick set of laminae is laid down by a single wave, then a minimum depth of 0.18–0.24 m would be required during the deposition of the clay sublayers. This depth is in relative agreement with the 0.24–0.29 m depth obtained in Table II and suggests either the clay density was a little lower or the concentration of solids was a little higher.

In Figure 5, the bedforms change from flat beds to cross beds, back to flat beds, as seen in B7, B8, and Layer C, respectively. This sequence first appears at Point W (Figure 8), where the cross beds are more prominent. The growth of the lowermost cross beds in Figure 8 appears to define the growth on the top and lee slope of a single dune. The top of that growing dune (right edge of photo) is similar in height to the top of another dune (from left); thus it appears that depth limited the ultimate height of the cross beds. If the maximum height of the cross beds in B8 is 20 cm, it would require a flow depth of 1.2–1.6 m to produce a ratio of 6:1 to 8:1. A comparison of elevation from the bottom of B8 at Point W with Figure 3 shows it to be almost equal to mean sea level in the levee. The full height of an additional 1.2–1.6 m on top of this would all be above mean sea level and certainly require the added depth of the storm surge and thus could only have been laid during the passage of such a wave.

If the cross beds of B8 represent the passing of a single wave, sedimentation occurred in a remarkably short time. Since a similar bedform was not produced by each cycle of waves, something unique occurred there. One explanation would be the failure of the levee's steel sheeting and broadening of the breach, providing the space for increased volume of flow in the neighborhood with the resulting depth increase and space for canal scour in the breach and the remarkable resulting quantity of clay in B8.

Figure 8 shows the angle of the cross beds of B8 decreasing upward as they approach the topmost laminae of the migrating dune from the left. As the splay built, depth limited further growth, as flow separation could no longer take place. Figure 12 shows the transition from high-velocity flat beds to dunes is "gradual." McKee et al. (1967, p. 836, brackets added) considered "low-angle foreset bedding [5°–10°]…along the outer margins of the sand sheet" to be the first sign of decreasing velocity. Decreasing depth pushed the flow down into this "gradual" transition zone.

The abrupt boundary at the top of B8 suggests a definite break or change in sedimentation. It is not a reactivation surface, which many books illustrate as a termination of cross bedding for a time, followed by its resumption (Nichols, 1999; McLane, 1995). Instead, it is a flat gap, a small-scale version of those examined by Roth (2009), which are both large and extensive in the sedimentary sequences of the western United States. He notes little or no erosion or weathering at these gaps, despite there being reservoirs for vast lengths of time for secular geology.

A flat gap in the middle of flat beds in the Katrina splay was attributed earlier to a change in depth in a continuous, unidirectional current. No velocity change was needed. Therefore, while the flat gap does represent a real gap in time, it is a very short gap measured in milliseconds to seconds, after which sedimentation resumed. Thus the boundary at the top of B8 likely did not reflect changing velocity, which would have produced different bedforms. Rather, it probably indicates a depth change, possibly at the end of a storm surge wave—in this case, the first/primary wave in a continuing wave train. The following wave in the train would have been smaller and less powerful (Figure 13).

Nichols (1999, p. 42) echoed a largely shared opinion: "The bed of sand which is formed from a decelerating flow will show a reduction in grain size.… Flows which gradually increase in strength through time … produce reverse grading." In other words, velocity changes are shown by grain size. However, McKee et al. (1967, p. 850, emphasis and brackets added) concluded that "stages in development of flood deposits may be recorded at any particular place by changes in the structure [bedforms] of sand. In contrast, the texture [diameter] of sand, although it may record rapid flow with relatively coarse grains and a decrease in velocity with finer grains *can be deceptive*." He repeatedly showed examples where coarse or fine sand in a rapidly accreting sequence was not a function of flow velocity but was more a function of sediment source. This is intuitive, though rarely considered; if only fine sand is available in a current, then nothing coarser will be deposited.

The only significant exceptions to this principle are sand surfaces of a deflation nature, winnowed of their finer fraction, or stable surfaces exposed to currents insufficient to move the coarse fraction, such as at the bottom of San Francisco Bay (Rubin and McCulloch, 1980) or eolian locations. However, none of these represent a rapidly accreting surface in a continuous, unidirectional current.

McKee et al. (1967, p. 850, emphasis added) recognized the intrinsic uniqueness of high-energy deposition:

> Strata of sand both in stream channels and on bordering flood plains, when deposited by a violent flood, contain dominantly horizontal layering characteristic of upper stream regimes. Much of the layering is in the form of fine laminae similar to the *type commonly ascribed to intermittent accumulation in quiet water over a long period of time*.

The Katrina splay deposits reinforce his observations and suggest that careless field interpretation of this type requires re-examination.

Layer C, with its two sublayers, is the deposit of two waves under conditions that limited the height. Formed of low-angle foresets, the slightly sloped laminae suggest this, as do the topmost ripples (Figure 9). Figure 14 illustrates the variety of possible bedform successions within the observed size range of splay sediments. Two different sequences are shown for fine sand. For the fraction > about 0.16 mm, the sand follows the sequence in Figure 12, flat beds to cross beds to ripples. Figure 12 was developed based on conditions beneath the double line at 0.25 mm in Figure 14. For the fraction < 0.16 mm, decreasing flow creates ripples atop flat beds.

The ripples at the top of Layer C at Point X (Figure 9) were possibly produced by decreasing velocity. While the transition from flat beds to ripples is appropriate for fine sand, close examination of Figure 9 suggests otherwise. The tops of the foresets with their low-angle cross-lamination extend directly up into the body of the ripples. Therefore, these are not ripples produced by decreasing flow but by wave ripples of the vortex variety (Nichols, 1999). These ripples are produced by high, sustained winds over the water surface, consistent with hurricane winds continuing after deposition. The sinuosity of the ripple crest, bending in front of the wall, is consistent with the wall's deflection of these winds.

What kind of ripples would be expected from decreasing velocity? McKee et al. (1967, p. 832) documented several locations at abrupt boundaries of deposition near preexisting banks, or "where receding water poured back into the main or subsidiary channels or where it swirled around the bases of large trees." There, flat beds shifted to low- to moderate-angle foreset bedding with *climbing ripple laminae* and convoluted structures. Nelson and Leclair (2006, p. 3) stated: "Spectacular cases of climbing dunes were seen on obstacles such as cars." These are probably similar to bedforms McKee et al. (1967) observed around trees and other obstructions, caused by velocity drops at these locations.

The low-angle foresets of Layer C suggest a velocity decrease during deposition. McKee et al. (1967) thought that a change from flat beds to low-angle foresets was the first indication of diminishing flow velocity. If W (total height 1.8 m) is 20 cm higher than X (total height 1.6 m), then at W the top of C1 would be only 30 cm below the normal mean canal surface level, giving a depth to height ratio of 10:1 for deposition of the 3 cm sublayer. At the top of C2, the same depth would be 27 cm, giving a ratio of 9:1. These numbers, while reflecting our uncertainty of the exact conditions at the time, provide ratios near the 6:1 to 8:1 range of Allen (1976).

Calculations in Table III may be underestimates, as the Froude numbers for the Manning velocities are somewhat under the 0.844 limit proposed by Kennedy (1963). That the conditions remained near this point is consistent with the findings of Grant (1997, p. 356, brackets added) who found that: "interaction between the water surface and bedforms … maintain competent flows in mobile channels to Fr = 1 [at or just below critical flow]." This condition is favored because it moves the maximum amount of water while "dissipating current energy." The areas swept clear of sediment suggests that conditions were near critical flow at all times. Table II Froude numbers are commensurate with those McKee et al. (1967) estimated at the Bijou Creek flood, which had a mean flow rate of 16.4 fps (5.0 m/s), a flow of up to 21.83 fps (6.65 m/s) in the main channel, and 11.8 fps (3.6 m/s) and a flow depth of 8–9 ft (2.5–2.75 m) with F_e = 0.74 in another location.

If these "planar strata" formed during high flow, but without distinct parting lenses at the cm scale or continuous distinct lamination expected from flume experiments with lower concentrations, then how did they form differently under hyperconcentrated flow conditions? Julien et al (1994, p. 8) explain how segregation of heterogeneous sediments takes place.

> Only the lateral motion of the mixture in any direction is necessary to induce segregation. During the lateral motion of the sand mixture … the fine particles fall through the interstices between the coarse particles and reach the bottom of the moving layer, while the coarse particles start rolling on top of the fine particles … After a certain time, the fine particles stabilize at the bottom of the moving layer while coarse particles remain mobile on top.

In a flume, dispersive shear stress caused by interaction between the solid particles is avoided by using low solids (Julien et al., 1994). This produces distinct continuous laminations but produces the slow growth progression of the bedform down the flume, requiring 20–30 minutes to build a thin layer of cross beds a few cm thick the length of the flume (Julien et al., 1994). This is consistent with their observation that "lamination becomes clearer as the rolling distance increases" (Julien et al., 1994, p. 9), with the clearest lamination being observed when the larger particles are allowed to form few-cm-thick cross beds.

But we need to understand how sedimentation varies with hyperconcentrated flows, when the dispersive shear stress is high and causes interactions between the solid particles, and the rolling distance for the larger particles is not great enough to allow clear lamination to form. Demonstrations in non-flume experiments with dry sediment mixtures of two different sizes or densities were shown by pouring or agitating in air (Julien et al., 1994). Many mixtures showed distinct separation based on size or density differences and rolling distance. A spectacular illustration was performed by Berthault, who put a wet heterogeneous mixture of sediments into a funnel, swirled it, and drained the water out the bottom (Berthault, 1988, p. 2). He produced a stack of laminae clear up the sedimentary column (Figure 15).

I believe that when a hyperconcentration is composed of a heterogeneous mixture of sedimentary materials, turbulence vectors do not interact equally with coarse and fine grains within the total depth of flow. Coarse grains will move more than fines by both Bernoulli forces and turbulence (McLane, 1995). Sorting of the heterogeneous mixture may begin wherever turbulence vectors are most dampened, but at concentration where solid particle interactions exceed dispersive shear stress, particle interactions will initiate incipient segregation through all levels of the flow.

As in producing the sets of laminae we recognized when reviewing the

τ_*	% solids	τ_{01} N/m^2	S	h, m	Manning V_1 m/s	Bray V_1 m/s
0.044	0.05	47.5	0.0032	1.4	3.54	4.1
	0.09	45.3	0.0032	1.25	2.44	3.8

Table III. Calculated results based on maximum clast size (d_b = 0.07 m) in predominantly clay layers and differences in percent solids. Depth (h) and velocity (V) represent maximum conditions during storm surges.

Figure 15. Hyperconcentrated laminar bedforms produced by swirling a wet heterogeneous sediment mixture and drawing the liquid out the bottom. Note large number of "laminar strata" produced atop each other in an instant of time. From Berthault (1988, figure 1).

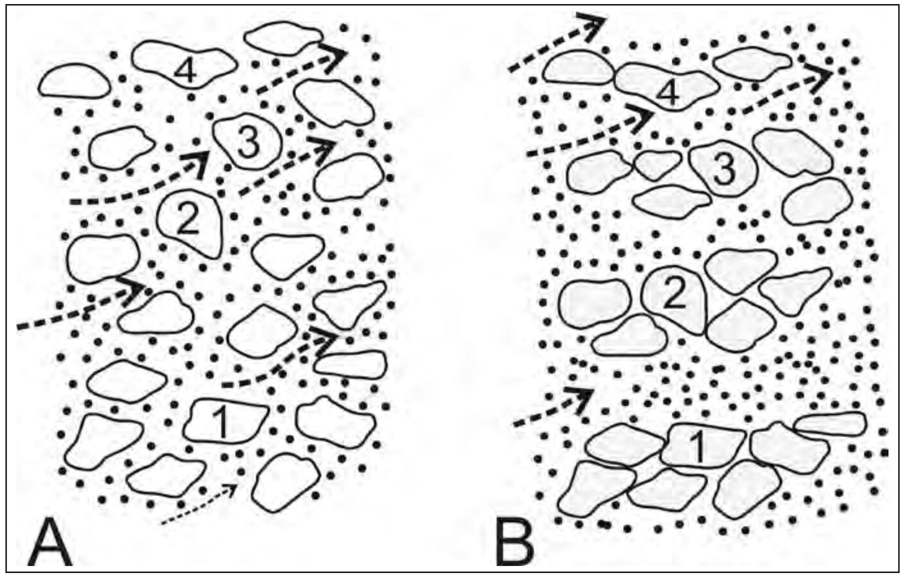


Figure 16. Segregation of particles under hyperconcentrated conditions begins when turbulence brings particles into contact. Larger particles will start to cohere more rapidly than smaller particles. When cohesive forces exceed viscous and shear forces, the larger particles aggregate, deflecting turbulence and moving closer together until they form distinct layers around multiple growth nuclei in multiple layers throughout the water column, not just on the bottom as under normal conditions. An incipient pavement forms, restricting smaller particles, which begin to collect on the pavement's upper surface. Because sedimentation is rapid, some fines remain as matrix, but most form layers between the coarser laminae. Since each layer is self-organizing around its own growth nuclei, the chances for a cm-scale lamination to grow continuously in all directions are limited due to the available sediments.

observations of McKee et al. (1967) of Bijou Creek, the production of stacks of laminae in a set needs an explanation. If a hyperconcentration of particles produces a high frequency of interactions between the particles, we can expect incipient segregation to begin in multiple stacked levels. This will result in distinct multiple moving layers—each with its own population of rolling and falling particles. Once segregation begins, the aggregate of large particles will form a pavement that traps small particles and blocks smaller turbulence vectors. Thus it begins to generate its own boundary layer. This, in turn, creates a series of cohesive and viscous sublayers and separate turbulence vectors maintaining layer integrity and prolonging roll time. This allows fines to migrate downward; thus each aggregate is able to grow with coarser particles on its undersurface (Figure 16).

Julien et al. (1994, p 8) noted that it is a continuous interaction of "fine particles … [which] reach the bottom of the moving layer … while coarse particles remain mobile on top," but as a result of the concentration, it is happening simultaneously on many levels in the flow with only abbreviated rolling distance for each particle.

This is significant because it means that sets of discontinuous laminae can form together. Interaction between cohesive and viscous forces limits the thickness of laminae that can form within given conditions of solids concentrations and depths. The 6:1 to 8:1 ratio of flow depth to laminae thickness used above should be applied to an entire set of laminae produced under hyperconcentrated conditions. Cross bedding produced under these conditions may actually deposit the set of laminae in sets that will break off and slip down the stoss slope. That would account for relatively regular interspersing of clay drapes in cross bedding (Figures 8 and 11) and provide the presence of clay drapes as an indicator of hyperconcentrated conditions.

In the Katrina splay deposits, the low-angle foresets of Layer C represent the first indication of a decrease in velocity, but because multiple boundary layers existed simultaneously at discrete levels within the current, flow separation over the total depth did not occur. Formation of new laminae took place preferentially at the lead surface of the hyperconcentrated flow, and the reduced velocity allowed the laminae set there to settle faster than it formed, producing low-angle foresets. Convoluted bedding formed when the flow decreased below the threshold of forming linear lamination. Thus, low-angle foresets and convoluted bedding are a progression produced in a hyperconcentrated flow under conditions of decreasing velocity without formation of a dune with a lee slope.

What will form is a set of mm-scale laminae that are irregularly discontinuous both parallel and perpendicular to flow. Parting laminae are present at the mm scale but are discontinuous because of the constant alternation of coarse and fine layers, and the interruption of one lamina by another forming simultaneously at another loci. Individual aggregates of large particles and clusters of such aggregates together form a single boundary layer with an irregular flat form and perimeter, so a cross section through the deposit shows randomly arranged, stacked, flat laminae less extensive on the cm scale. These characteristics of hyperconcentrated laminar bedding would place it as a subcategory of hyperconcentrated flood-flow deposits as defined by Smith (1986). As a group, hyperconcentrated flood-flow deposits, and hyperconcentrated laminae are distinct in other examples in the rock record, indicating high concentrations of solids, high velocity, and relatively shallow flow depths. Clearly, this diagnostic tool would be significant in diluvial investigations.

In summary, high-flow regime flat beds are produced over a range of solids concentrations, but the actual form varies with concentration. At ~ 5% solids, hyperconcentrated laminar bedforms are produced in sets without clear parting layers at the mm scale. This unique appearance is diagnostic of hyperconcentrated conditions. McKee et al. (1967, p. 850) observed that they are "similar to the type commonly ascribed to intermittent accumulation in quiet water over a long period of time." Given the radically different depositional conditions, it is imperative that they be distinguished from other flat beds in the field.

Mudstones and shales were once thought to represent quiescent sedimentation. Schieber et al. (2007) have demonstrated otherwise. Their work is supported by the Katrina splay deposits: even at high velocity, clay ovoids and floccules will form by cohesion and be deposited as distinct cm-scale laminae in regular sets of flat beds. Concentration of clay leads to the formation of floccule streamers and in turn to large, continuous sheets of clay. It seems logical that if floccule streamers are forming, and increasing clay concentration increases streamer size, then increased distance will result in larger sheets, perhaps equivalent to the "rolling distance" for the separation of bed load.

Hyperconcentrated laminar bedforms are laid down in sets whose characteristics are determined by the depth of the energy surge added to a continuous unidirectional current. Greater depth deposits thicker sets. Surges vary both depth and flow energy, and changes can occur as rapidly as the passage of individual waves. Even if depth remains the same, a change in energy will be seen as a small flat gap in the continuously depositing column.

Successive sets will only show interruptions for incidental events overlaid on the unidirectional steady flow and the wave surges. These include variations in sediment composition, flow eddies, obstructions, or, as was seen in New Orleans, the effect of wind on the water surface. Incidental time markers, such as pebble impressions or repeated patterns of deposition are the only obvious indicators of set separation, and they may be used to fix a mean set size indicating flow depth and the rate of deposition per wave.

Conclusions

A canal breach caused by Hurricane Katrina resulted in deposition of 1.8 m (5.9 ft) of sediment in a New Orleans neighborhood. This splay deposit shows that the variety and sequence of both sediments and bedforms are equally important in discerning the depositional conditions. Although the splay covers less than 0.003 km^2 (0.0011 mi^2), its hydrodynamic information can be extrapolated to much larger deposits in the rock record.

Despite features commonly attributed to low, slow flow, the splay deposits were clearly formed by sedimentation in a continuous unidirectional current, overlaid by storm surge waves. Published accounts provide a maximum time of 46 minutes for sedimentation, and a more likely minimum of 2–3 minutes is established, based on the wavelength of the storm surges. Sediment source played an important role. Significant changes in velocity or fluctuations of an active/passive cycle of sedimentation cannot be supported as occurring without diagnostic changes in bedform. The occurrence of clay layers or minor erosional surfaces in an otherwise continuous, rapidly accreting bedform can no longer be considered to reflect such a change in velocity. Clay sheets occur as clay drapes in cross beds or sheets between laminae, both expected from experiments on heterolithic stratification, and both deposited in the high-velocity current, not times of low current flow. Therefore, without significant additional evidence from the sediments or the bedforms to the contrary, the occurrence of clay sheets or layers in the sequence should no longer demand a chronostratigraphic horizon.

The splay deposits also demonstrated that flat beds can be succeeded by cross beds and then revert to flat beds within a continuous, single, unidirectional current, caused by depth variations under constant flow. They also show that a sequence of wave-deposited bedforms, which could easily be interpreted in the rock record as long periods of time, can be the product of continuously depositing waves, in sequence. Under conditions of continuous deposition, the waning stage of the wave will leave some evidence in the bedforms. Under hyperconcentrated conditions, that evidence may be as small as a low-angle increase in the laminae.

Grain size strongly influences bedforms. Different grain sizes will produce different sequences. A bedform or series of bedforms will not necessarily display graded upwards lamination if the smaller grains are not available or if the roll time is not adequate for such a clear separate bedform to occur. Hyperconcentration of solid particles is a common situation under which clear parting layers will not be produced by increase rolling time.

As long as an adequate source of both current and sediment is maintained, these small splay deposits show that a sedimentary pile of great thickness can accumulate rapidly in shallow water under hyperconcentrated conditions. Furthermore, it suggests that when hyperconcentrated laminar bedforms are present, the measured rate of deposition will be only a few minutes per meter of sediment. This rate is elevated relative to current thought and will vary with flow, obstructions, depth, and sediment source. These can be deciphered only by examining the range of bedforms in a given formation. Furthermore, rates may rise even more as we use hydrodynamics to properly discern these conditions—using them to broaden our understanding of sedimentation during the Genesis Flood.

Finally, this evaluation demonstrates the superiority of a hydrodynamic analysis to interpretation in terms of facies models. No facies model was applicable to the splay deposits, and that should raise questions about other sediments in the rock record. This is another argument for a different approach to the rock record: abandoning the facies model system and working out the mechanics of deposition instead. Likewise, these deposits show that carefully arranged bedforms are not produced in a haphazard manner. The physics of sediment transport and deposition in moving water are well known and provide hard guidelines for the required physical conditions associated with particular bedforms. Although much about diluvial processes is not the same as those occurring today, the physics of deposition are, and thus the Katrina splay deposits provide a real modern analog for ancient deposition. Speculative environmental scenarios that exceed the available data are a poor substitute for rigorous scientific analysis of the sediments found in the rock record, blinding geologists to the need for more accurate, but more difficult quantitative sedimentological analyses.

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