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Sedimentary signature of Hurricane Isaac in a *Taxodium* swamp on the western margin of Lake Pontchartrain, Louisiana, USA

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Abstract Compositional and geochemical profiles were established for a 59-cm sediment core extracted from a small pothole pond in a *Taxodium* (bald cypress) swamp 830 m inland from Lake Pontchartrain in south-eastern Louisiana, USA. The core consists of a top organic unit (peat to clayey peat) from 0–29 cm above a bottom clay unit at 30–59 cm depth. Four distinct zones, marked by gradual changes in organic content and elemental concentrations, occur in the clay unit. These changes probably reflect two cycles of slowly changing water depths. Hurricane Isaac's signature, a brown clay band at 3–5 cm, is identified based on the stratigraphic and compositional correspondence with the storm's event layer, documented from nearby sites. Sedimentary and geochemical similarities between this material and clastic bands at 15–19 and 23–25 cm identify those two intervals as potentially representing earlier floods. The Cl/Br ratio presents a potentially useful method for distinguishing fluvial and marine flooding.

Key words paleotempestology; Lake Pontchartrain; Cl/Br ratio; Hurricane Isaac; sedimentary signature

INTRODUCTION

The coast of Louisiana is an extremely dynamic region, prone to rapid and dramatic ecological, hydrological, and geomorphological changes. The various mechanisms driving such changes are of both natural and anthropogenic origins, and operate across a large spectrum of timescales (Day *et al.*, 2007). Although over centennial to millennial timescales this has resulted in a spatially variable pattern of land gain/land loss (Kolb & van Lopik, 1966), over the past few decades the overall effect has been massive coastal erosion (Barras *et al.*, 2008). Erosion and coastal retreat is expected to continue over the 21st century (Blum & Roberts, 2009). This land loss often occurs in pulses, driven by the occurrence of tropical cyclones, especially intense hurricanes (Dingler *et al.*, 1995; Chabreck, 1988; Flocks *et al.*, 2009). The geomorphic effect of such storms is complex, resulting in both depositional and erosional features. Although these storms often transport large amounts of offshore sediments onshore (Cahoon *et al.*, 1995; Turner *et al.*, 2006; Williams, 2009, 2012; Liu *et al.*, 2011), they can also drive the coast landward by eroding barrier islands (Dingler & Reiss, 1995), converting salt marsh to open water, fresh marsh to salt marsh, and significantly damaging the bottomland hardwood forests farther inland (Doyle *et al.*, 1995; Jackson *et al.*, 1995). These effects are extremely variable spatially due to the intense heterogeneity of the Louisiana coast (Guntenspergen *et al.*, 1995), and the overall sedimentary benefit of tropical cyclones is far from clear (Turner *et al.*, 2006; Törnqvist *et al.*, 2007).

The extreme variability of both the sedimentary signatures of hurricanes along the Louisiana coast and the elevational benefits derived from such sedimentation makes it an important objective to identify and document such signatures over as wide a range of geological and ecological environments as possible. Although several studies have investigated such signatures along the northern Gulf of Mexico across a number of different environments (Liu & Fearn, 1993, 2000; Lambert *et al.*, 2008; Liu *et al.*, 2008, 2011; Reese *et al.*, 2008; Williams, 2009, 2012), all such studies have been conducted in areas immediately adjacent to the coast. In this study we examine the sedimentary signature of Hurricane Isaac (2012) in a *Taxodium* (bald cypress)-dominated wetland immediately west of Lake Pontchartrain, ~70 km from the open Gulf, in order to both expand our knowledge of hurricane-generated deposition in an inland setting and to evaluate the possible long-term geomorphic effects of hurricane sedimentation for the location.

STUDY SITE

The Pontchartrain Basin is one of the largest estuaries in the northern Gulf of Mexico, draining an area of ~44 000 km^2 in Mississippi and Louisiana (Flocks *et al.*, 2009) (Fig. 1). The northern two-thirds of the basin overlies Pleistocene terraces, while south of the Baton Rouge–Denham Spring fault trend the southern third occurs above lower-lying Holocene material (Flocks *et al.*, 2009). This lower section consists of two large bodies of open water, Lake Pontchartrain and Lake Maurepas, surrounded by extensive wetlands. Although significant areas of bottomland hardwood forest and fresh to brackish marsh exist, the wetlands are dominated by a *Taxodium-Nyssa aquatica* (water tupelo) swamp forest. The larger, Lake Pontchartrain, semi-oval in shape with a surface area of 1632 km^2 (Penland *et al.*, 2002) and an average depth of 3.7 m (Li *et al.*, 2008), connects to the sea through three narrow passes to the east. Lake Maurepas, smaller and fresher, with a surface area of ~240 km^2 and an average depth of ~2 m (Bianchi & Argyrou, 1997) lies to the west and connects with Lake Pontchartrain through the narrow Pass Manchac. The Mississippi delta plain development has been driven by the formation and abandonment of a number of overlapping lobes (Kolb & van Lopik, 1966) over the mid to late Holocene. One of these, the St. Bernard lobe, active from *c.*4000–1000 BP, pushed the coastline to the east during six separate pulses, with its northern boundary forming a barrier situated along the present southern edge of Lake Pontchartrain, resulting in the formation of Lake Pontchartrain, Lake Maurepas, and the surrounding wetlands in the low area between this ridge and the Pleistocene terraces to the north (Frazier, 1967; Flocks *et al.*, 2009). Progradation of the lobe ceased *c.*2000 BP and subsidence followed the abandonment of the lobe *c.*1000 years BP.

This area frequently experiences flooding both from tropical storms, including major hurricanes (Day *et al.*, 2007), and river floods, especially those resulting from the breaching of artificial levees since the mid-1850s (Keddy *et al.*, 2007). Despite the passage of a large number of

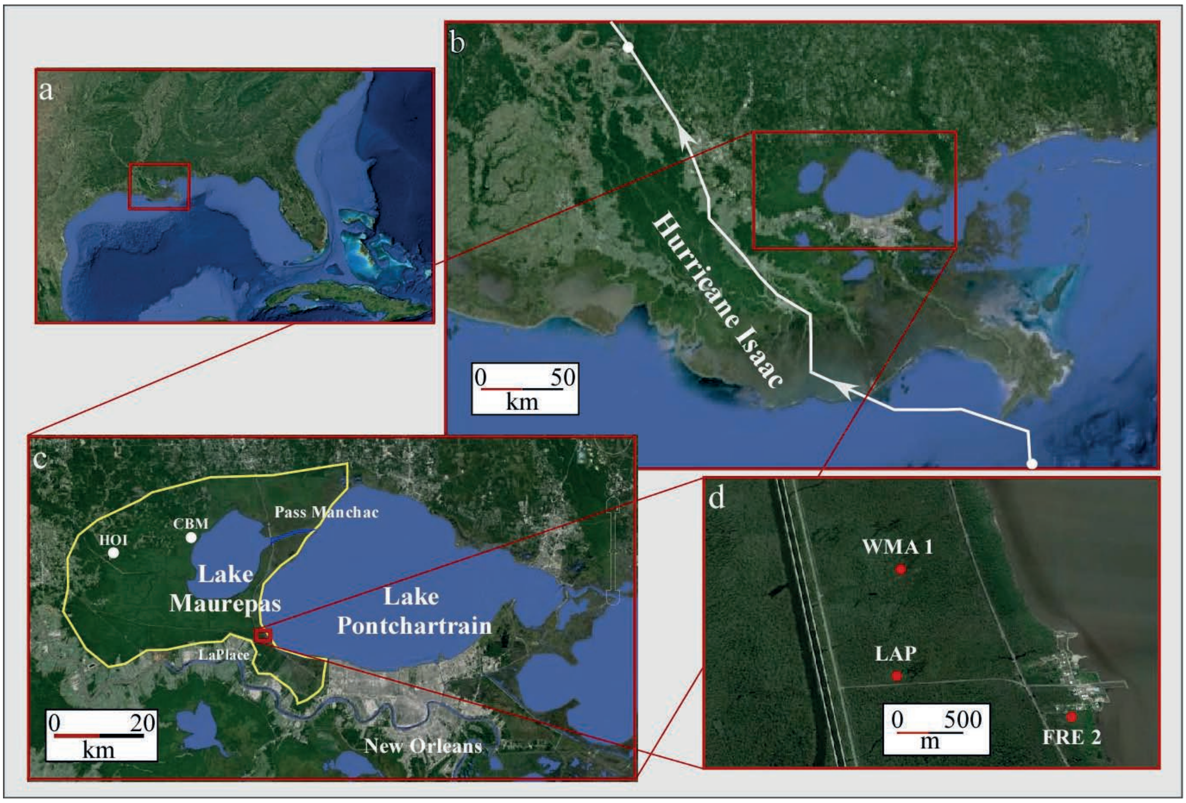

Fig. 1 Location of the study site. Google Earth imagery displays the location of: (a) the northern Gulf of Mexico, (b), southeastern Louisiana, (c), the western margin of Lake Pontchartrain, (d) the locations of cores WMA 1, LAP and FRE 2. The two white dots marked on the storm track in (b) show the forward movement of Hurricane Isaac during a 36 hour period.

recent tropical cyclones (Hurricanes Katrina and Rita in 2005, Hurricane Gustav in 2008, and tropical storm Lee in 2011), the flooding associated with Hurricane Isaac (2012) was unprecedented for the area, resulting in the closing of the interstate highway (I-10) just to the west of Lake Pontchartrain and the evacuation of several neighbourhoods in the nearby community of LaPlace (Boquet, 2012; Thibodeaux, 2012).

We extracted core WMA 1 on 7 February 2013 from a *Taxodium*-dominated swamp within the Maurepas Swamp Wildlife Management Area immediately inland from the southwestern edge of Lake Pontchartrain (Figure 1c). The core was extracted from a depth of ~ 1 m from a pothole pond, 830 m inland from Lake Pontchartrain (Fig. 2).

Fig. 2 WMA 1 coring site. The core was extracted from the bottom of a small pothole pond in a *Taxodium* swamp.

Hurricane Isaac

Hurricane Isaac was a low category 1 hurricane, with a maximum sustained wind speed of 130 km/h when it made landfall near the Mississippi River mouth on 28 August 2012 (Berg, 2013) (Fig. 1(b)). The storm's large size (tropical-storm-force winds extended >590 km at landfall) and slow forward movement (~300 km over a 36 h period) (Fig. 1(b)) resulted in heavy rainfall (>50 cm in New Orleans) (Berg, 2013) and up to 45 hours of tropical force winds in some coastal areas (Berg, 2013). The storm track resulted in heavy northeasterly winds driving vast quantities of water westward across the shallow Lake Pontchartrain, piling water against the western shore and pushing it though Lake Maurepas and the entire Lake Pontchartrain Basin wetlands. Combined with the heavy fluvial input from inland areas, many areas that had not previously experienced flooding during recent tropical cyclones were inundated and record flood levels recorded for many areas (Berg, 2013).

METHODS

Core WMA 1 is a composite core, with the top section (0–35 cm) extracted by a 7.62 cm diameter aluminium push tube, while the bottom section (36–59 cm) was extracted by means of a Russian peat borer. The core sections were extracted from slightly offset sites with a 30-cm overlap. The peat borer section was photographed in the field, after which both core sections were hermetically sealed before being transported to the Global Change and Coastal Paleoecology Laboratory at Louisiana State University, where both sections were stored in a cold room at 4°C. The core location was marked by a handheld GPS. When opened, the core sections were again photographed, described stratigraphically using the Munsell Color Chart, and subjected to loss-on-ignition (LOI) analysis following the method of Liu & Fearn (2000) to determine water, organic, carbonate and residual percentages at 1-cm resolution. Water weight is reported as percentage of wet weight, while organics, carbonates, and residuals are reported as percentage of dry weight. Elemental concentrations were determined by a Delta Premium DP-4000 X-ray fluorescence (XRF) analyser at 2-cm resolution, with the results reported in parts per million (ppm). The device is calibrated by comparison with two certified standards (NIST 2710a, 2711a). A Cl/Br ratio was generated based on the concentration counts (ppm), and not mass, as is sometimes done.

RESULTS

Core sediments vary from peat to clay. The top 28 cm of WMA 1 is a dark brown peat to clayey peat layer containing numerous roots and plant fragments, with organic content up to >50%. Within this section, two bands of more mineral material occur at 3–5 cm (21–25% organic) and 15–19 cm (20–23% organic) (Figs 3 and 4). Although these two intervals have similar organic, water and carbonate profiles, the Cl/Br ratio is much higher for the layer at 3–5 cm, a light brown clay layer (top, Fig. 4). A less pronounced dip occurs at 23–25 cm (19–24% organic). Below this, the transition to the underlying grey clay is abrupt, with organic percentage dropping from 23% to 10% at 27–29 cm depth. Four zones can be distinguished within the lightly laminated grey clay that dominates the sediments below 29 cm. The section from 29–36 cm is a smooth, brownish-tinted light grey clay containing many small (<1 mm), unconnected, unidentifiable organic fragments (lower left, Fig. 4). The interval at 36–45 cm is slightly more organic (>10%), browner in colour, with slightly larger organic fragments, including a few rootlets. In the brownish-grey, rootless clay interval at 46–52 cm organics drop to 4%, with a corresponding decrease in size and abundance of plant fragments. The bottom section, from 53–59 cm, is much more organic (>17 %) and browner, containing many larger organic fragments, with the lowest few mm consisting of a nearly peat-like material (lower right, Fig. 4). Changes in elemental concentration closely parallel the stratigraphic changes (Fig. 3). Concentrations of most elements (Ca, K, Ti, V, Cr, Fe, Co, Zn, Rb, Zr, Sr and Ba) and Cl/Br ratio values are much higher in the clay section than the organic section, and within the clay (29 cm and below) are lowest in the two zones with elevated organic content. The reverse is true for Br, which achieves higher values in the organic sections.

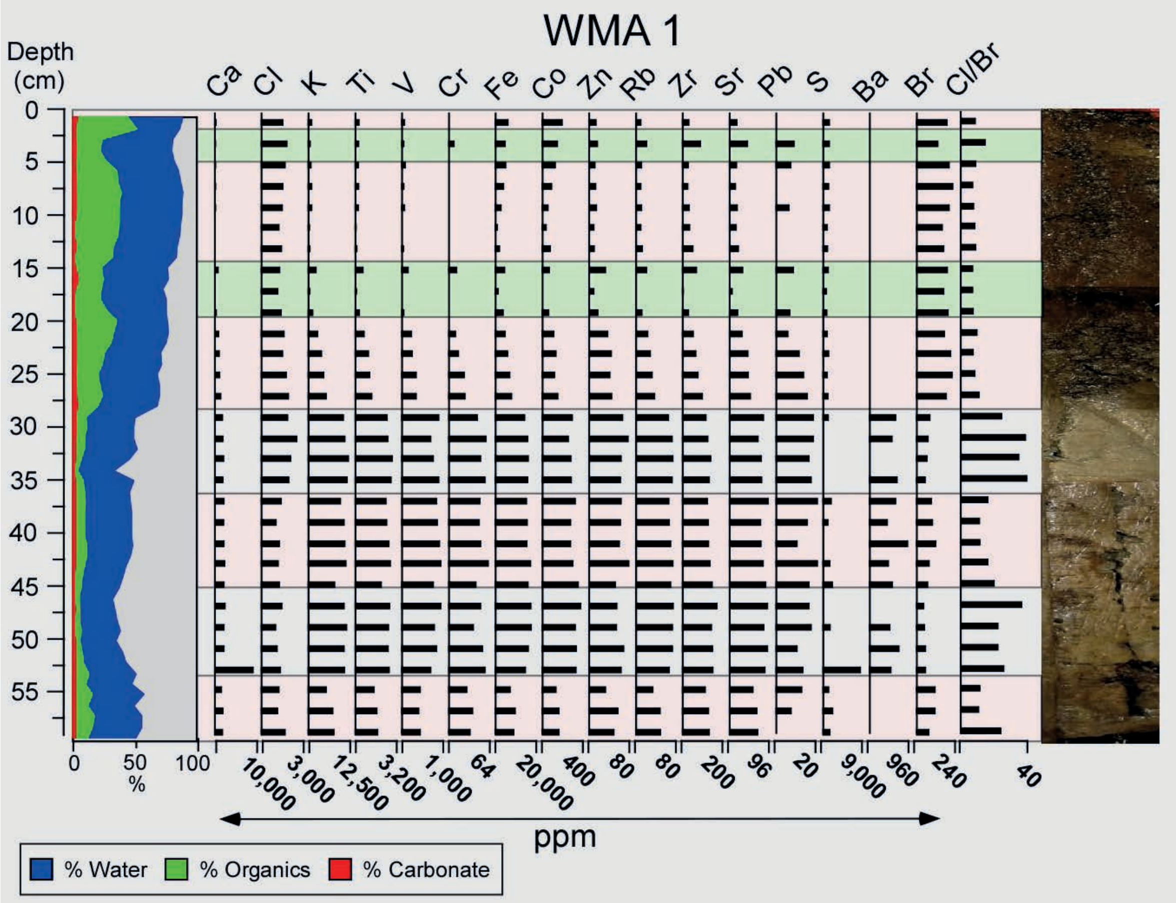

Fig. 3 Core WMA 1. LOI graph is on the left, showing percentages of water, organics and carbonates. Elemental concentrations in ppm are shown in the centre and a core photograph is displayed on the right. The red shading highlights intervals of elevated organic content, the green shading outlines the Isaac layer (3–5 cm) and a possible earlier flood event.

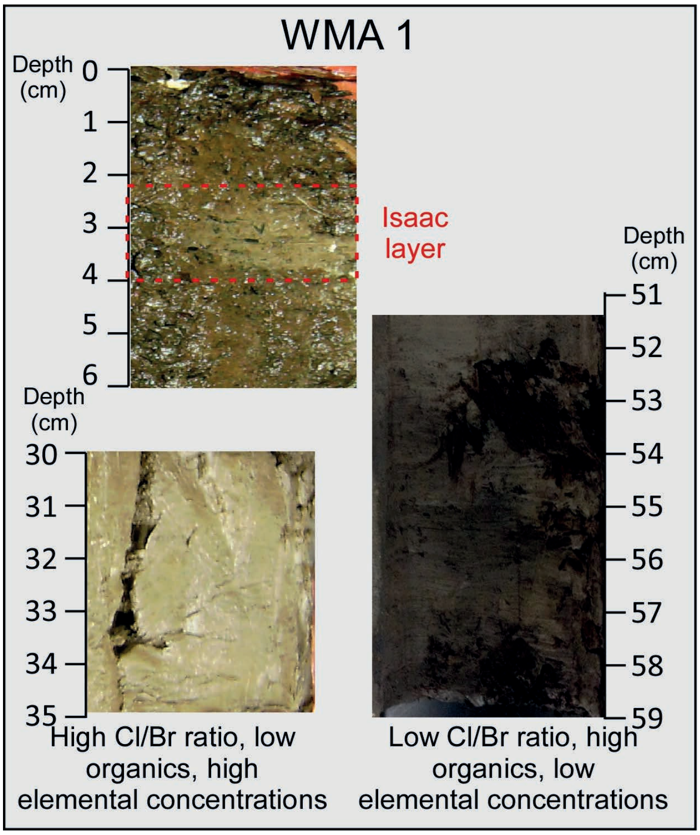

Fig. 4 Sedimentary differences. Photos show representative sediments from the organic unit (top), low-organic clay (bottom left), and slightly higher organic clay (bottom right).

DISCUSSION

Hurricane Isaac storm deposit

The sedimentary signature of Hurricane Isaac has been identified from several inland locations near our site. Significant amounts of the short-lived radioisotope ^{7}Be were found to be present in anomalous surface mud layers in all material tested from three widely separated locations within the Lake Pontchartrain basin. This material includes two core tops from HOI (Fig. 1), a bottomland hardwood forest ~16 km west of Lake Maurepas and 39 km west of Lake Pontchartrain (Kam-biu Liu, unpublished data); two core tops from CBM, a *Taxodium*-dominated swamp ~4 km west of west of Lake Maurepas and 20 km west of Lake Pontchartrain (Lambert *et al.*, 2014); and a core top and surface sample from LAP, a very similar *Taxodium* swamp ~800 m south of our transect and ~1100 m west of Lake Pontchartrain (Liu *et al.*, 2014) (Fig. 1(d)). In all but one case this unconsolidated, root-free mud layer overlies a distinct layer of forest litter that includes intact leaves. The presence of detectible amounts of ^{7}Be isotope, which has a half-life of 53 days, indicates that the mud layer was deposited over a very short time period shortly before collection. As all samples were collected 29 days after the passage of Hurricane Isaac, the most reasonable interpretation is that this layer was deposited by flooding associated with that hurricane. ^{7}Be analysis was not conducted on WMA 1 as it was not collected until >5 months after the passage of Hurricane Isaac. However, the brown clay band at the top of the core (top, Fig. 4) matches the mineral layer found in the other three sites both stratigraphically and visually. Like them, it corresponds to a small dip in the LOI curve and sits immediately above a more organic layer. However, because the core was extracted from the bottom of a small pothole pond, the underlying material is an organic mud layer, rather than a relict forest litter layer. A similar dip at 15–19 cm possibly represents an earlier flooding event.

Clay layer

Although the clay section below 30 cm resembles the Hurricane Isaac event layer in that both present as dips in the LOI curves, the resemblance goes no farther. Sedimentological evidence argues strongly against the deposition of the clay by any form of high-energy event. Although thick sedimentary deposits have been documented for historical levee breaks (Keddy *et al*., 2007), any event powerful enough to deposit 30 cm of sediments can be expected to leave some sedimentary markers such as abrupt grain size changes, upward fining sequences, a series of obvious compositional changes, rip-up clasts, erosional contacts, chaotic vertical deposition, buried forest litter, and debris layers that commonly distinguish high-energy events. None of these features occur within the clay, which is remarkably uniform, with no distinguishing features beyond light laminations, small horizontally-oriented colour changes, and gradual changes in organic content (Figs 3 and 4). The recognition of four, incrementally different sedimentary units within the clay section supports the view of normal deposition under low-energy conditions. Although the overall change from the bottom of the core (lower right, Fig. 4) to the top of the clay section (lower left, Fig. 4) is dramatic, the change is both gradual, and bi-directional, marked by two cycles of rising and falling organic levels (Fig. 3). The XRF profiles also display small gradual changes, generally in concert with changes in the organic content. Such slow, secular changes are the hallmarks of a slowly changing environment, not a large, instantaneous high-energy event.

Similar arguments eliminate the possibility that these clays were deposited as crevasse splays by the St. Bernard delta lobe, as such depositions are marked by even more dramatic and abrupt sedimentological transitions. Although a chronology has yet to be established for WMA 1, the basal date for the 59 cm core is most likely far younger than the date of *c*.2000 BP established for the termination of the progradation of the St. Bernard delta lobe.

Environmental change

Although we interpret the clay section as representing a period of two cycles of gradually increasing and then decreasing organic content under generally stable environmental conditions, the abrupt sedimentological, compositional, and elemental changes that occur across the transition between the clay and the organic sections imply a large and rapid change in the sedimentary environment. The differences in the elemental concentrations, particularly the Cl/Br ratio, above and below the transition are especially striking. The top organic interval was most likely deposited under conditions similar to the present; i.e. a pothole pond in a *Taxodium* swamp. Conditions during the period of clay deposition can be inferred by a close examination of the sedimentary data. The light laminations indicate deposition under water, which the lack of *in situ* roots indicates was fairly deep and open. The small grain size indicates low energy conditions. Combined, these characteristics indicate that the clay was probably deposited during periods of deeper water. The gradual compositional changes suggest that conditions remained relatively stable throughout the period. The two cycles of increasing/decreasing organic content most likely resulted from small fluctuations in water level, with deeper periods corresponding to lower organic levels.

Cl/Br ratio

Using the Cl/Br ratio as an indicator of salinity provides a possible method of identifying the source of these water level changes. The Cl/Br ratio for seawater is 655:1 (Alcalá & Custodio, 2004), and 100:1 to 300:1 for precipitation (Davis *et al*., 1998). Therefore, changes in these ratios, which are unaffected by evaporation, should correspond to the relative influence of seawater and freshwater in different core intervals. There is a clear correlation between the Cl/Br ratio and sediment composition, with much higher values occurring below the organic/clay transitions. Even the small increases in organic levels occurring in the clay section correspond to large decreases in the Cl/Br ratio (Fig. 3), indicating that clay percentages and salinity have a positive relationship.

During the period of maximum mineral percentages the Cl/Br ratio achieves values of 40:1, which is 6% of the seawater value. This is in line with Lake Pontchartrain's brackish nature, with mean salinity varying from 5.4 to 1.2 ppt, depending on location (Sikora and Kjerfve, 1985). Given our site's location on the western margin of Lake Pontchartrain, this suggests that periods of deeper water correspond to increased influence of lake water at the coring site. If the surface water at our site is a mix of fresh (fluvial, precipitation) and brackish (Lake Pontchartrain) water, periods of elevated lake level relative to the coring site should result in a higher Cl/Br ratio, and lower lake levels should result in a lower ratio. This would explain the relationship between ratio values and organic content, as both would be controlled by water depth.

A similar stratigraphy of a top organic layer overlying a thick, rather featureless clay that extends to a depth of 1 m, has been documented in a core extracted from LAP, ~800 m to the south and at similar distance from Lake Pontchartrain (Liu *et al.*, 2014), perhaps providing evidence that water level changes covered a relatively large area.

The Cl/Br ratio also potentially provides a window for examining the origin of flood events. The clastic layer at 3–5 cm, attributed to Hurricane Isaac, has a much higher ratio than does the suspected event layer at 15–19 cm. These differences in ratio values perhaps reflect relative differences in the strength of the fluvial and marine input of individual events, possibly providing a means of distinguishing fluvial and marine events and/or estimating the relative importance of storm surge *vs* precipitation for events associated with tropical cyclones.

CONCLUSIONS

A clastic band situated at a depth of 3–5 cm has been identified as having been deposited by Hurricane Isaac. This band has distinct sedimentary features, contrasting sharply in colour (lighter brown), composition (clay *vs* clayey peat), elemental concentrations, and water and organic content from the embedding material. Two similar clastic layers at 15–19 and 23–25 cm possibly represent earlier flooding events. More precise information concerning these older events is not possible at this time given the multitude of possible precipitating events (levee breaks, fluvial floods, tropical cyclones, and heavy precipitation events). However, the Cl/Br ratio may provide a tool for determining the relative influence of seawater and freshwater in specific events, thereby helping to identify the origin of the flood, which in this location can originate in either the east (Lake Pontchartrain) or the west (Mississippi River).

Core stratigraphy revealed two distinct sedimentary units; an organic unit at the top, and a bottom clay unit. We interpret the surface organics to have been deposited in a wetland environment, probably closely resembling present conditions. The bottom unit was probably was deposited during periods of generally deeper water. Two subdued cycles of elevated organic deposition occurred during this period, probably associated with smaller decrease in water level. The Cl/Br ratio displays a high sensitivity to organic levels, probably establishing a more direct record of Lake Pontchartrain surface level changes.

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