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Harry F. L. Williams

Chelsea E. Beaubouef

Kam-biu Liu

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Research Paper

Testing XRF identification of marine washover sediment beds in a Coastal Lake in Southeastern Texas, USA

Harry F.L. Williams [a,*], Chelsea E. Beaubouef [a], Kam-biu Liu [b], Nicholas Culligan [b], Lance Riedlinger [b]

[a] Department of Geography and the Environment, University of North Texas, Denton, TX 76203, United States of America
[b] Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803, United States of America

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ABSTRACT

This study tests the ability of a novel approach to identifying washover beds in coastal lakes. Combined X-Ray Fluorescence (XRF) and cluster analysis was used to identify hurricane washover beds in sediment cores from Clam Lake on the McFaddin National Wildlife Refuge in southeastern Texas. The lake is known to contain washover beds from recent hurricanes, but the washover sediment has similar microfossil, loss-on-ignition and textural characteristics to non-washover sediment and is not readily distinguishable. Sediment cores taken from marshes surrounding the lake do contain visually-recognizable sandy washover beds of Hurricanes Ike, Rita, Carla and Audrey. XRF analysis of these washover beds, combined with cluster analysis, was used to construct "elemental fingerprints" with the potential to detect washover beds in the lake. Results are promising: multiple washover beds were detected in the lake and tentatively attributed to recent hurricanes. In some lake cores, washover beds likely to be present were not detected by the XRF/clustering technique; in other lake cores, up to nine washover beds were detected. The variation in the number of washover beds probably resulted from bioturbation, identification of two or more washover beds in a single washover deposit, and washover beds resulting from smaller storms. Valuable outcomes of this study are; 1) it confirms the presence of washover beds in the lake; 2) it provides greater insight into the number, stratigraphic position and thickness of washover deposits; 3) it identifies periods of heightened and diminished overwash activity, and 4) it provides a means of estimating the contribution of washover deposition to sedimentation in the lake. An additional unexpected finding is that long-term sedimentation rates derived from the lake and marsh cores closely match the rate of local sea-level rise, suggesting that sea-level rise may drive sedimentation in the study area.

1. Introduction

Coastal wetlands are threatened by global sea-level rise and reduction in sediment supply caused by artificial structures (Blum and Roberts, 2009). Recent studies have attempted to quantify the contribution of hurricanes to surface accretion in coastal wetlands, with the hope of encouraging coastal management strategies that promote hurricane-induced sedimentation (Bianchette et al., 2016). Williams and Flanagan (2009) studied the contribution of Hurricane Rita's storm surge deposition to long-term sedimentation in coastal marshes and woodlands in Cameron Parish, Louisiana. Hurricane Rita's storm surge sedimentation extended about 400–500 m inland and was up to 0.5 m thick (Williams and Flanagan, 2009). The thickness of Hurricane Rita's storm surge deposit is the equivalent of a decade to over a century's worth of non-storm-surge sedimentation (Williams and Flanagan, 2009).

The long term impact of sediments derived from hurricanes has been difficult to quantify over large areas. However, Tweel and Turner (2014) quantify the long-term contribution to soil inorganic matter for three hurricanes, Rita, Katrina, and Gustav, across coastal Louisiana. They found that for the Chenier plain and the 80% of the Louisiana coast that consists of abandoned delta lobes, hurricane storm surge sedimentation is the leading source of inorganic sediment. By using hurricane activity from the past 84 years to model longer-term hurricane activity, Cahoon (2006) estimated that 40,000 tropical cyclones have made landfall in the Gulf of Mexico region during the Holocene. This suggests that hurricane-derived sedimentation is a major source of sediment input for these coastal regions.

The amount of storm surge sediment that is delivered into coastal

* Corresponding author.
E-mail address: HarryF.Williams@unt.edu (H.F.L. Williams).

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environments is dependent upon a hurricane's ability to generate sufficient surge height and waves with enough energy to transport sediments. Major factors that affect storm surge are the hurricane's intensity, the distance from the site to the eye of the storm, position in relation to the hurricane, and configuration of the coastline. Also, the availability of sediment and the presence of local natural and artificial structures (dykes, foredunes, canals) that have the ability to enhance or diminish storm surge, will play a role in the amount of sediment delivered (Williams and Flanagan, 2009).

Significant progress has been made in identifying hurricane washover sediments in coastal environments. A common approach in coastal geomorphological and paleotempestological studies is to identify and date washover beds within lakes, marshes and lagoons (Donnelly et al., 2004; Liu and Fearn, 2000; Williams, 2010). This approach is based on the idea that a hurricane storm surge will transport and deposit coarser allochthonous material onto finer, more organic-rich, low-energy "non-storm" sediments, resulting in an anomalous and distinctive sand layer. There are multiple established proxies used for identifying washover beds, such as loss-on-ignition (LOI) and micropaleontological analysis (Liu and Fearn, 2000; Liu et al., 2008; Lu and Liu, 2005; Wang et al., 2019; Williams, 2010).

Loss-on-ignition can be used to estimate the moisture, organic matter and carbonate content within a sediment sample (Liu and Fearn, 2000). The use of LOI as a proxy to identify hurricane layers is based on the assumption that the washover layer will have more sand and carbonates and less moisture and organic content then "non-storm" sediment regularly deposited in coastal wetlands (Oliva et al., 2017). Yao et al. (2018) describe hurricane Rita and Ike washover deposits on the southwestern Louisiana coast as distinct light-colored calcareous sediment layers within brown clay. Both storm deposits contained a small amount of quartz sand and gravel, some foraminiferal tests, and shell fragments. The LOI data reveals that the brown clay has relatively high moisture (>50%) and organic matter contents (>10%), whereas the Rita and Ike washover beds have low moisture (10–20%) and organic matter (<5%).

Over the past decade, a number of geochemical-based proxies have also been introduced (Oliva et al., 2017; Ramírez-Herrera et al., 2012; Yao et al., 2019; McCloskey et al., 2018). X-ray fluorescence (XRF) is a nondestructive analytical technique that can determine the elemental composition of sediments. It is a well-established technique that allows sediment cores to be scanned at high precision. This technique has been used in numerous studies to identify tropical cyclone washover sediments. However, the elemental signature of washover deposits varies across studies. Ramírez-Herrera et al. (2012), for example, in a study of extreme wave deposits on the Pacific coast of Mexico, found that two washover sand units within clayey silt contained silicon (Si), potassium (K), phosphorus (P), strontium (Sr), barium (Ba), zirconium (Zr) and calcium (Ca). An increase in Si and K within the sand units was attributed to an increase in quartz and feldspar. This is consistent with beach sand, suggesting the sand unit came from a nearby beach environment. An increase in Sr, Ba, and Ca in the sand units suggests a marine influence, particularly Sr and Ba, which are usually present in higher concentrations in seawater than freshwater (Ramírez-Herrera et al., 2012). Yao et al. (2019), in a study of Hurricane Harvey sedimentation on the mid-Texas coast used 9 common elements, including the chlorine (Cl)/bromine (Br) ratio. They noted that Fe (iron) and Ti (titanium) are examples of elements that have been used successfully as terrestrial runoff indicators. Sr and Ca are typically abundant in saltwater and are used as indicators of marine intrusion (McCloskey et al., 2018).

Woodruff et al. (2009) focused on using Sr as an indicator of storm deposits because it can be found in high concentrations within algal material, marine shells, and coral. The Cl/Br ratio has also been used as a marine indicator (Liu et al., 2014; Yao et al., 2019). Yao et al. (2019), in a study of Hurricane Harvey washover sedimentation, contend that washover sediments can be identified by an increase in the Cl/Br ratio. Cores collected from the San Bernard National Wildlife Refuge, Texas, did not have distinct sand layers, presumably due to a relatively weak storm surge; however, they concluded that the elevated Cl/Br ratio found in sediments near the top of each core provided a record of marine flooding (Yao et al., 2019).

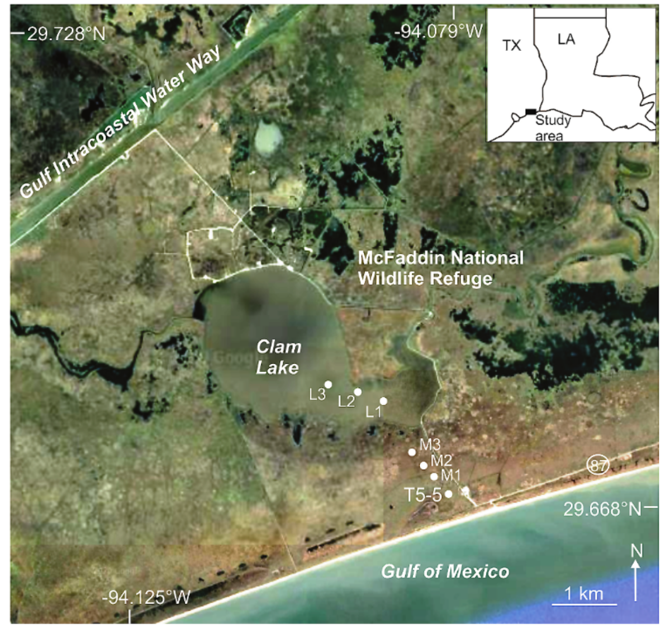

Fig. 1. McFaddin National Wildlife Refuge. Locations of sediment cores are shown. L: lake cores; M: marsh cores. Google Earth image, 2019.

This study presents results of a test of XRF analysis to discriminate between marine washover beds and "non-hurricane" sediments within the bed of Clam Lake on McFaddin National Wildlife Refuge (MNWR), in southeastern Texas. The refuge is known to contain washover deposits from four recent hurricanes – Ike (2008), Rita (2005), Carla (1961) and Audrey (1957) (Hodge and Williams, 2016). The objective of the study was to conduct XRF analyses of marsh cores, which are known to contain the four washover beds, and use the XRF "signatures" of the washover beds to identify hurricane washover deposits in cores from the bed of Clam Lake. The XRF component of the study uses cluster analysis to explore the discriminative capabilities of various combinations of elements present within the sediments.

This research fills a conceptual gap in knowledge because using XRF to identify hurricane washover sediments in a coastal lake bed is a novel application for this new analytical tool.

1.1. Study area

McFaddin National Wildlife Refuge is located in southeastern Texas in Jefferson County, about 20 km southwest of Sabine Pass (Fig. 1). The refuge consists of 238 km^2 of marshes and lakes and is generally classified as irregularly flooded estuarine intertidal emergent wetlands. Elevations on the refuge typically range from 0 to 1 m NAVD88 (Williams and Liu, 2019). Clam Lake, at ~4.4 km^2, is the largest lake in the refuge and is approximately 1200 m inland from the Gulf of Mexico shoreline. Numerous ditches connect the lake to the Gulf Intracoastal Waterway and Sabine Pass and the lake is classified as a tidally-influenced brackish lake (Williams, 2010).The lake is approximately at sea level making it the lowest elevation within the study area.

Previous studies on MNWR have identified and described hurricane washover beds in marshes and lakes on the preserve. Williams (2010) characterized Hurricane Ike's storm surge sedimentation in terms of stratigraphy, foraminiferal content, organic content and sediment texture. Thirteen pits were excavated along a transect from the shore to inland, allowing washover and marsh sediments to be studied and

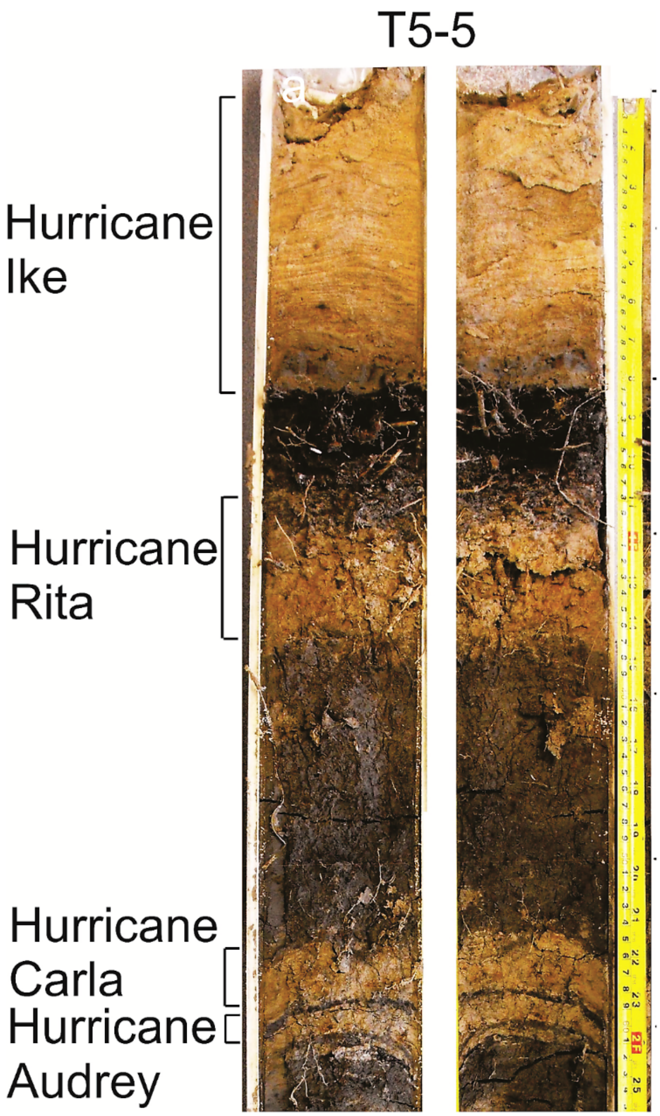

Fig. 2. Hurricane washover beds in core T5–5 (from Williams and Liu, 2021).

sampled. In addition, six cores were collected from Clam Lake. The Hurricane Ike washover deposit was thick, sandy and of low organic content near the shore and became thinner, less sandy and more organic farther inland. The cores collected from Clam Lake had no distinct sand layers and appeared as a uniform grey sandy mud. Offshore foraminifers, presumably transported inland by the storm surge, were common in the washover deposits in the marsh and in the lake, but foraminifers were not found in lower parts of lake cores suggesting that foraminifers are not well-preserved in these environments.

Hodge and Williams (2016) cored the same 13 pit locations used in Williams' (2010) study. Up to four distinct sand beds were visible within the cores. Hurricane Ike's deposit was near the top of every core; the other three sand beds were visible in some, but not all cores and the lowest two sand beds appeared mixed together in some cores. Recorded storm tides and wind speeds, combined with microfossil analysis, LOI, and Cesium-137 dating were used to confirm that the lowest three sand beds were Hurricane washover deposits and ascribe them to Hurricane Rita (2005), Hurricane Carla (1961) and Hurricane Audrey (1957) (Fig. 2). The presence of these sand beds in the marsh south of Clam Lake suggests that corresponding washover deposits are likely present in the lake bed.

Findings by Williams and Liu (2019) suggest that flood sediment carried into marshes by terrestrial flood waters may also be present in marshes and in the bed of Clam Lake. Hurricane Harvey (2017) flood deposits were found to be widespread on MNWR. The flood sediments are generally fine-grained, have relatively low sand contents and moderate organic contents. On some parts of the refuge flood deposits have similar LOI profiles to marsh deposits.

2. Methods

2.1. Field work

Sediment cores were obtained from the marsh by using a sledge hammer to drive thin-walled aluminum tubes into the marsh surface. Cores were secured in the tubes either by a retaining device at the bottom of the tube or by a vacuum seal device inserted into the top of tubes before retrieval. Coring tubes were retrieved by truck jack.. Excess tube was sawed off and duct tape was used to seal the tubes before transport to the laboratory. The three marsh cores were collected approximately along the same transect used by Williams (2010) and Hodge and Williams (2016). The location of each core site was recorded by hand-held GPS (Fig. 1). All three marsh cores experienced compaction, averaging 26%. Compaction does not affect recognition of washover beds within the cores or the XRF-based elemental analysis. Values derived from sediment thicknesses, such as stratigraphic position, were corrected for compaction by increasing measured thicknesses by 23%, 30% or 25% (for cores M1, M2 and M3, respectively). The lake sediments were much softer and more easily penetrated than the marsh. Lake cores were obtained by manually pushing core tubes into the lake bed; based on comparison of the depth of penetration of the core tubes and the length of resulting sediment cores, negligible compaction occurred.

2.2. Lab analyses

In the laboratory, cores were cut in half lengthwise; one half of each core was sampled at 1-cm intervals for LOI Analysis; the other half of each core was transported to the Louisiana State University Global Change and Coastal Paleoecology Lab where cores were analyzed at 1-cm intervals using X-ray fluorescence (XRF) analysis.

2.2.1. Loss-on-ignition

For consistency, the LOI procedures used in the lab followed recommendations of Heiri et al. (2001). The cores were sampled at 1-cm intervals, a portion of each sample was placed in a crucible, the rest was placed in a bottle. The subsample in the crucible was weighed and heated in a muffle furnace at 105 degrees Celsius for 24 h then reweighed to allow calculation of moisture content. The same subsample was returned to the furnace at 550 degrees Celsius for 4 h and then reweighed to determine organic matter content; the subsample was again returned to the furnace at 950 degrees Celsius for 2 h to determine carbonate content. The subsample in the bottle was weighed and then wet sieved through a 63-um sieve. The sand residue was air dried and weighed again to calculate the sand fraction, as a percentage of dry sample weight.

2.2.2. X-ray fluorescence

A handheld Olympus Innov-X Delta premium XRF analyzer was used to scan the cores. The cores were analyzed at 1-cm intervals for 90 s to identify concentrations of elements within the sediments. This method has the potential for human error. Inconsistency occurs in accurately identifying the starting point (0 cm) of the core, especially when vegetation was present, as well as trying to align the handheld scanner with each cm of core. These alignment uncertainties result in minor depth variations between XRF graphs, LOI graphs, and photographs. Additionally, the 1-cm resolution of the scanner means that finer stratigraphic details (e.g. a sand layer of a few mm thickness) cannot be precisely targeted, possibly resulting in a "mixed" signal from the

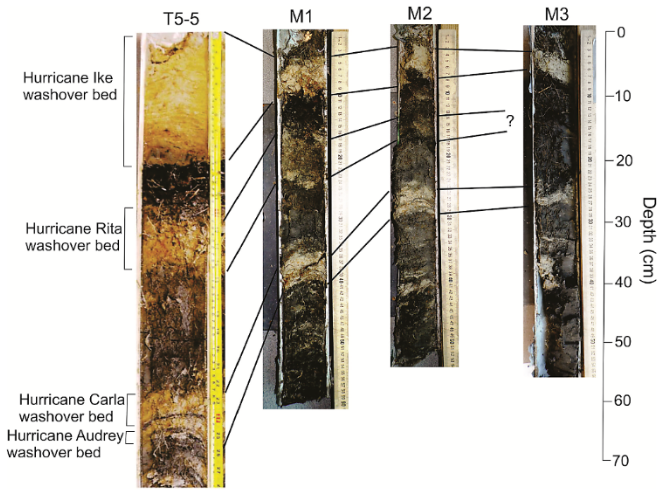

Fig. 3. Cores T5–5, M1, M2 and M3, showing correlation of visible sandy washover beds. Cores are not shown at their correct horizontal or vertical spacing. Question mark (?) denotes absence of visible Hurricane Rita washover bed in core M3.

scanner. These potential errors probably introduce some uncertainty into the XRF findings but are unlikely to obscure the overall results. A total of 16 elements were detected in the 6 cores (Sulfur (S), Cl, Ca, Sr, Zr, Br, K, Ti, Fe, vanadium (V), manganese (Mn), chromium (Cr), zinc (Zn), rubidium (Rb), barium (Ba), lead (Pb).

2.2.3. *Cluster analysis*

Hierarchal cluster analysis (HCA) was used to determine the effectiveness of XRF in distinguishing between washover and marsh sediments. Prior to clustering, elemental data was normalized to unit range (0–1) to prevent elements with large numeric concentration values from dominating in distance-based clustering functions (Suarez-Alvarez et al., 2012). HCA is able to group together samples based on similarities in their elemental compositions. The analysis produces a range of clusters, depending on the sensitivity of clustering; in this case, two to six clusters were selected for output. The approach to selecting elements used in cluster analysis was to identify elements that showed a contrast in elemental composition between known washover beds and enclosing marsh sediment in the marsh cores. A different set of contrasting elements was selected for each known washover bed (Ike, Rita and Carla/Audrey) in the three marsh cores.

3. Results

3.1. *Washover beds in the marsh cores*

Sandy washover beds are visible in the three marsh cores and correlate well with the known washover beds in core T5–5 from Hodge and Williams (2016). Hurricane Ike's washover bed is found within the upper 10 cm of the cores and has a thickness of 4–5 cm. Hurricane Rita's washover bed is visible in cores M1 and M2, but not in core M3. Hurricanes Carla and Audrey washover beds are visible in all three marsh cores, but rather than distinct layers (as in core T5–5) they are mixed together into a single layer, probably resulting from bioturbation (Fig. 3).

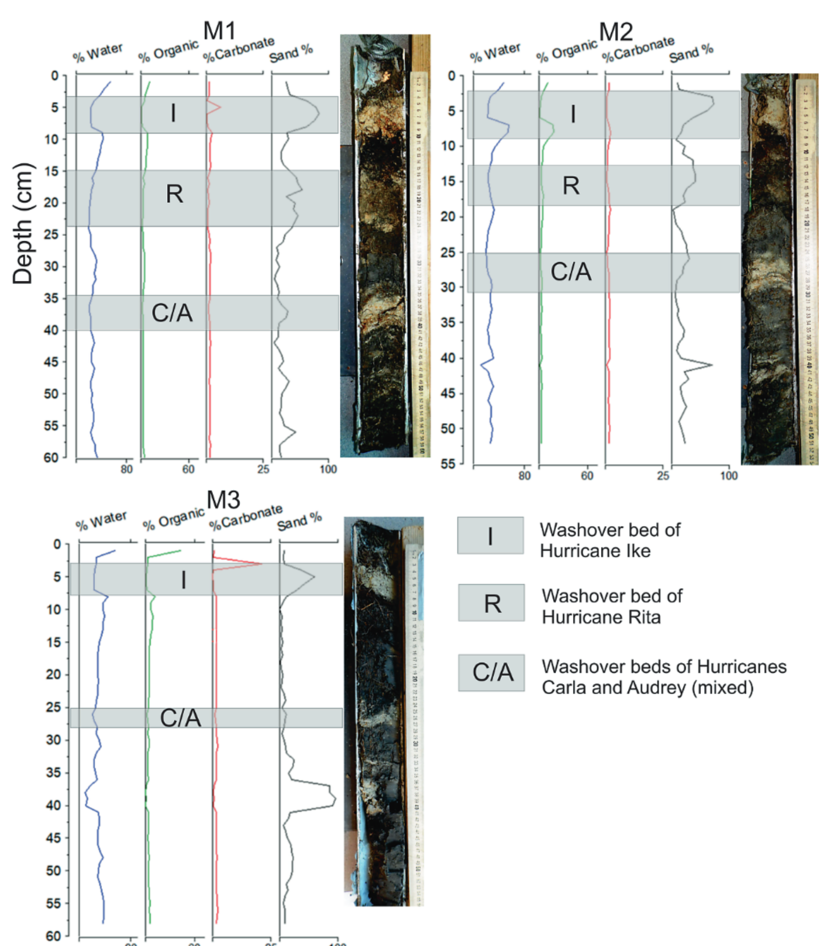

Fig. 4. LOI results for cores M1-M3. Grey bars represent known washover beds of Hurricanes Ike, Rita and Carla/Audrey.

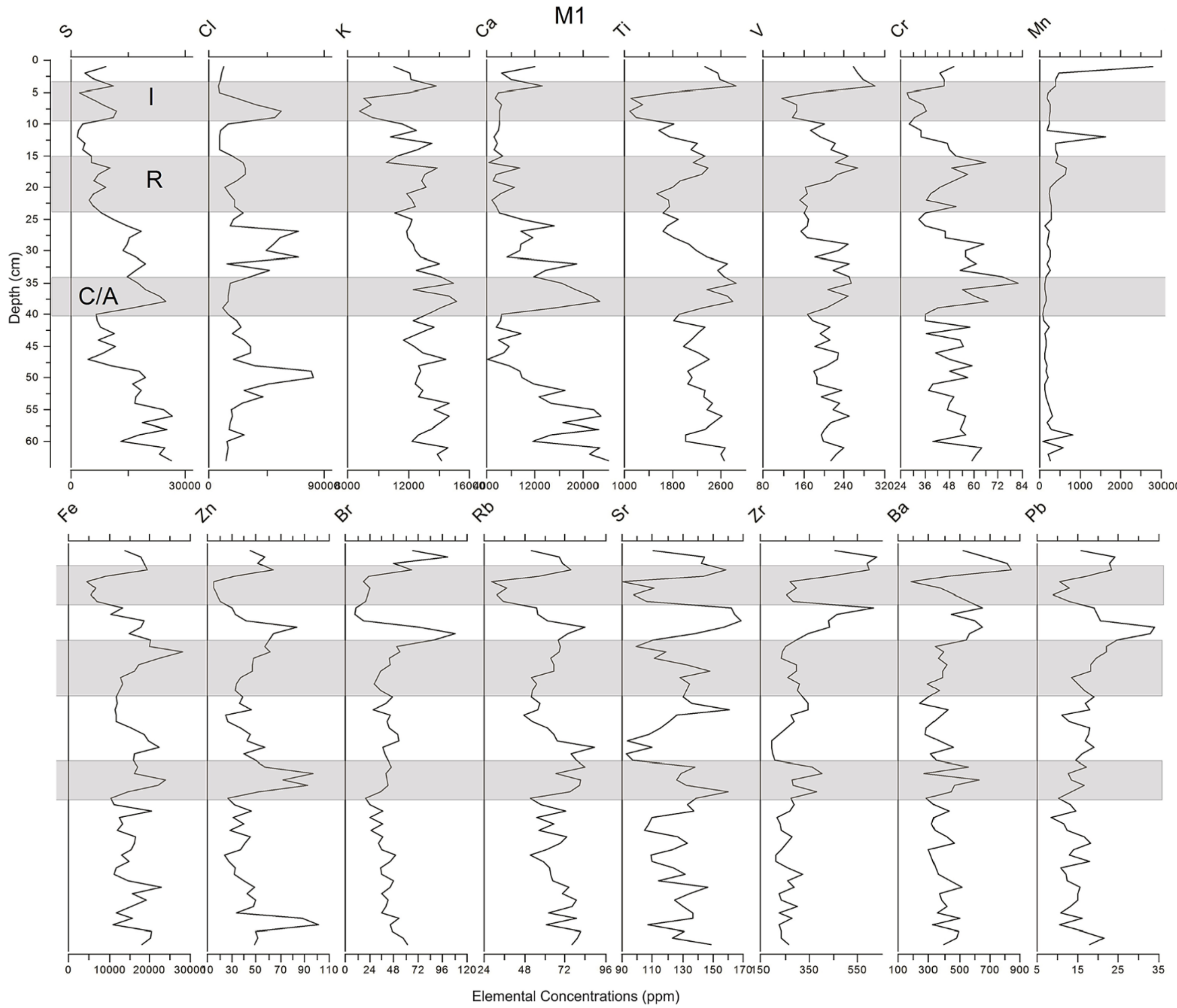

Fig. 5. Results of XRF analysis of marsh cores M1, M2 and M3. Grey bars represent washover beds (I: Ike; R: Rita; C/A: Carla/Audrey).

3.2. Loss-on-ignition

The LOI results confirm the presence of the washover beds in the three marsh cores. Hurricane Ike's sand bed is well-defined by peaks in sand content and marked declines in water and organic contents in all three cores. The mixed washover beds of Hurricanes Carla and Audrey have less pronounced LOI results, but small peaks in sand content and small declines in water and organic content correspond with the sand beds. Hurricane Rita's washover bed is visible in cores M1 and M2 and corresponds to peaks in sand content and declines in water and organic contents; however, a Hurricane Rita washover bed is not visible in core M3 and the LOI results do not support the presence of a bioturbated sand bed. Hodge and Williams (2016) found that Hurricane Rita's sand bed became sporadic with increasing distance inland, so it may be that little sand was deposited at the location of core M3 (Fig. 4).

3.3. XRF

XRF results for cores M1, M2 and M3 are shown in Fig. 5. "Distinguishing elements" for cluster analysis were defined as elements present at relatively high or relatively low concentrations in washover beds in contrast to the rest of a core, as shown in Table 1. Elements were selected if they were common to a washover bed in all cores; for example, distinguishing elements for Hurricane Ike are Ti, V, Cr, Fe, Br and Rb at relatively low concentrations. Hurricane Rita is distinguished by Ca, Ti and V at low concentrations and Fe at high concentration. Elements selected for Hurricanes Carla and Audrey are Sr and Zr at high concentrations (Table 1).

3.4. Cluster analysis

Cluster analysis was performed on the assumption that "distinguishing" sets of elements found in washover beds in the marsh cores will also be present in the lake cores and provide "elemental fingerprints" that can identify washover beds. It was further assumed that much of the lake cores consist of non-hurricane sedimentation, punctuated by periodic washover beds recording sedimentation generated by hurricanes and, possibly, other large storms. For each analysis, 2 to 6 clusters were produced and, in each case, a cluster was identified that matched the elemental "fingerprint" of a known washover bed. Fig. 6

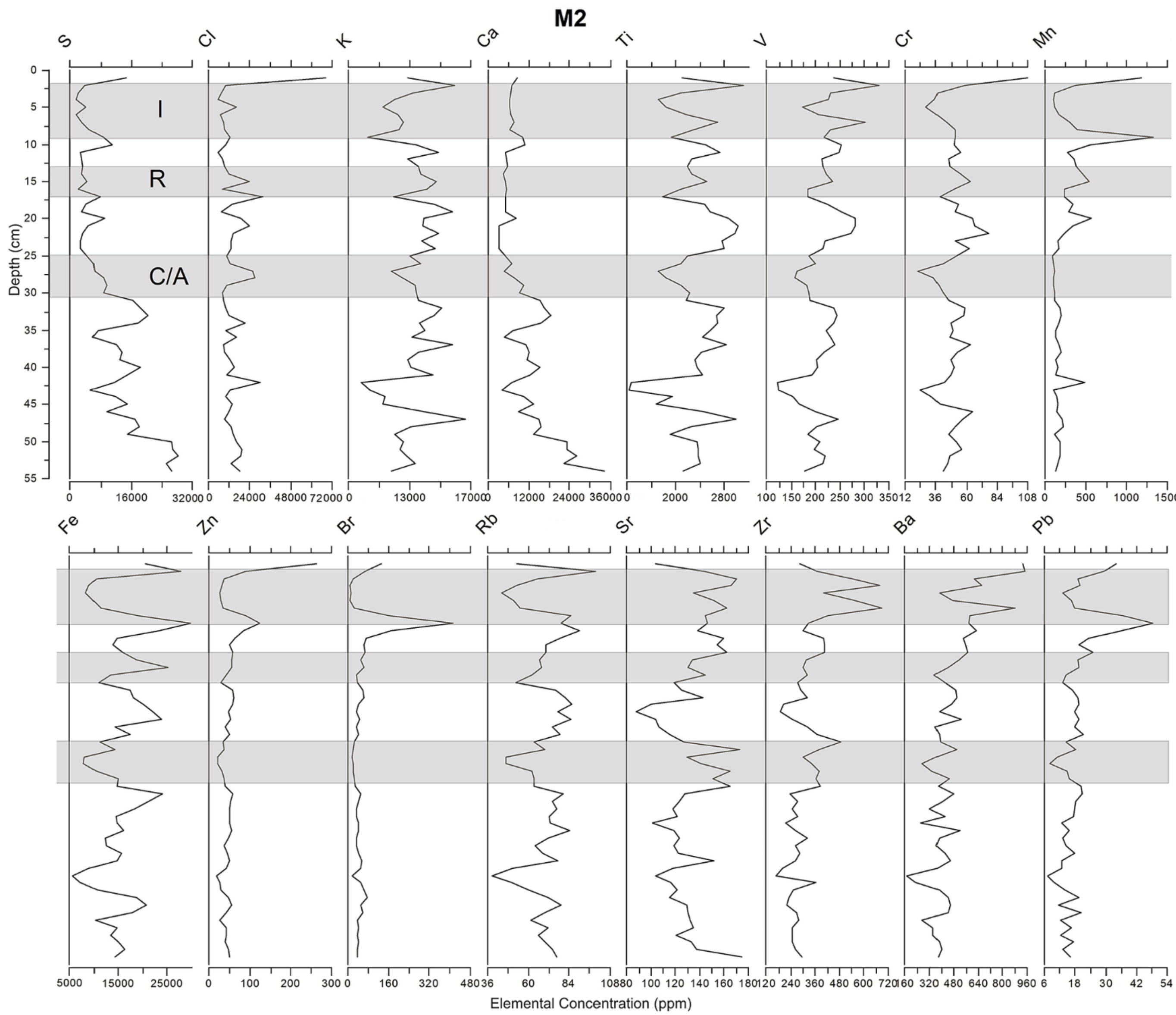

Fig. 5. (*continued*).

shows the resulting sediment clusters in the three lake cores that correspond to the Ike fingerprint (low concentrations of Ti, V, Cr, Fe, Br and Rb), the Rita fingerprint (Ca, Ti and V at low concentrations and Fe at high concentration) and the Carla/Audrey fingerprint (Sr and Zr at high concentrations). The combination of three cores and cluster analysis using three elemental "fingerprints" results in nine results, as shown in Fig. 6.

4. Discussion

The XRF results suggest that within-core elemental variability is greater than between-core elemental variability. For example, in core M1 elemental compositions of the three washover beds appear to have little in common; whereas in cores M1, M2 and M3, the Hurricane Ike washover bed has more elemental similarities, in that Ti, V, Cr, Fe, Br and Rb are at relatively low concentrations in the Ike washover bed in all three cores. This suggests there is no "universal" washover composition, but different compositions for parts of the same washover deposit and for washover beds of different hurricanes.

Many factors may account for these differences; for example fining of washover sediment with distance inland presumably changes the elemental composition because less sand and more mud and organics are present in the deposit. Another factor likely resulting in contrasting elemental compositions between washover beds is mixing of washover and marsh sediment perhaps during emplacement of the deposit or by post-depositional bioturbation. The washover beds of Hurricanes Carla and Audrey, for example, have clearly been mixed with marsh sediment, whereas Hurricane Ike's washover bed appears relatively undisturbed.

Cluster analysis identified multiple washover beds in each core; for example, using the Hurricane Ike elemental "fingerprint" resulted in identification of three washover beds in cores L1 and L2, and nine washover beds in core L3 (Fig. 6). While the beds at shallow depth probably record Hurricane Ike, the deeper beds must be other washover deposits with sufficient similarity to Hurricane Ike's washover composition to be placed into the same cluster. Likewise, using the Rita and Carla/Audrey "fingerprints" resulted in identification of multiple washover beds in the lake cores. Based on the stratigraphic relationships of the washover beds in the nearby marsh cores (Fig. 4), it is probable that the washover beds at shallow depth are associated with Hurricane Ike, the washover beds at intermediate depth are from Hurricane Rita and the deeper washover beds record Hurricanes Carla and Audrey. These tentative attributions are shown in Fig. 6.

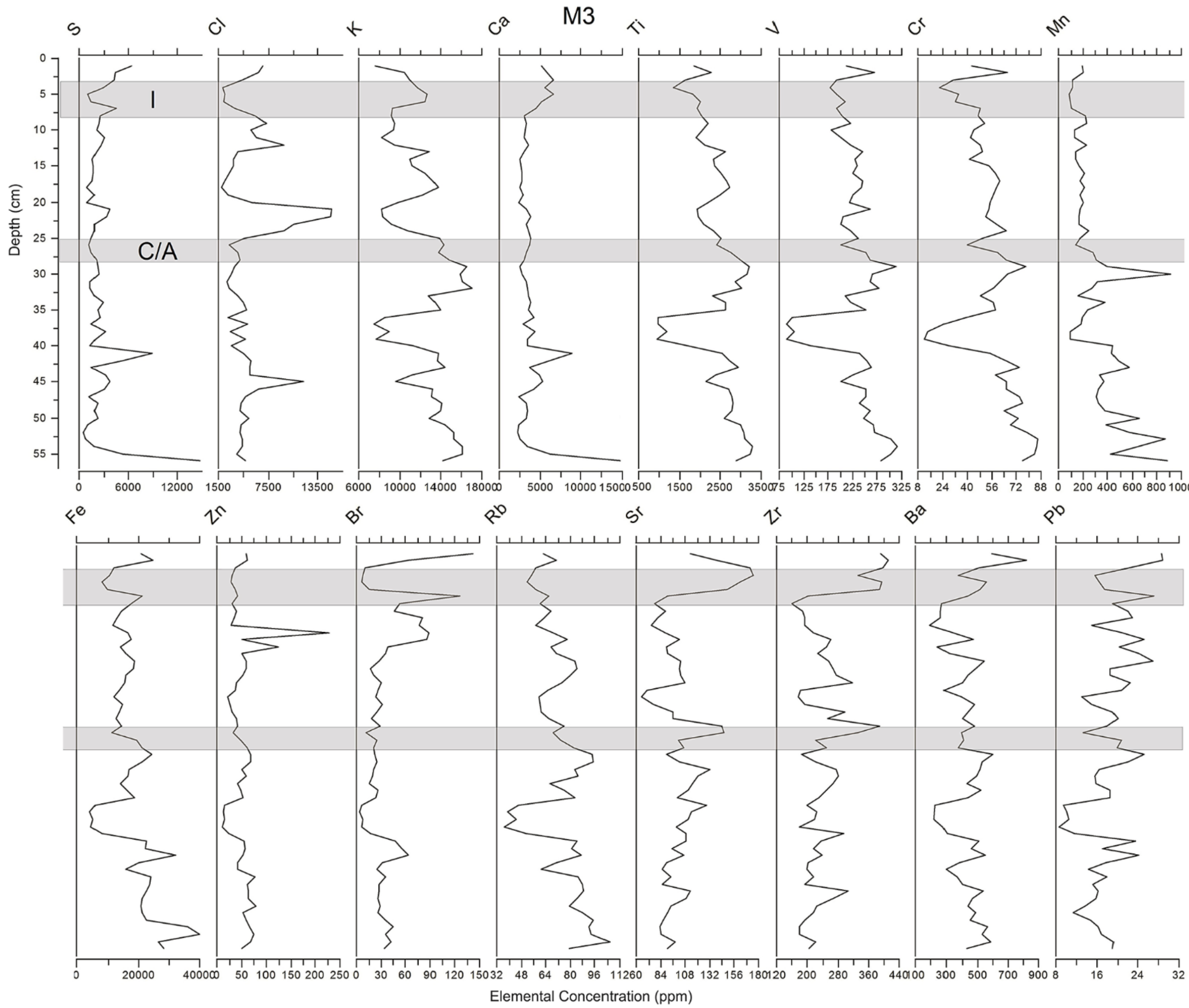

Fig. 5. (*continued*).

Table 1
Distinguishing elements in the washover beds of Hurricanes Ike, Rita and Carla/Audrey in cores M1-M3.

	CORE M1		CORE M2		CORE M3	
	High	Low	High	Low	High	Low
IKE WASHOVER	Cl	K, Ca, Ti[a], V[a], Cr[a], Fe[a], Zn, Br[a], Rb[a], Sr, Zr, Ba, Pb	Sr, Zr, Ba	S, Ti[a], V[a], Cr[a], Mn, Fe[a], Zn, Br[a], Rb[a]	Ca, Sr, Zr	Cl, Ti[a], V[a], Cr[a], Mn, Fe[a], Br[a], Rb[a]
RITA WASHOVER	Fe[b], Pb	Ca[b], Ti[b], V[b]	S, Mn, Fe[2]	Ca[b], Ti[b], V[b], Rb	N/A	N/A
CARLA/ AUDREY WASHOVER	S, K, Ca, Ti, V, Cr, Zn, Rb, Sr[c], Zr[c], Ba	Cl, Pb	Cl, Sr[c], Zr[c]	Ca, Ti, V, Cr, Fe, Rb	Cr, Sr[c], Zr[c], K	V, Br

"Distinguishing elements" defined as elements present at relatively high or relatively low concentrations in washover beds in all three cores.
[a] Distinguishing element common in Hurricane Ike washover in all three cores.
[b] Distinguishing element common in Hurricane Rita washover in both cores.
[c] Distinguishing element common in Hurricane Carla/Audrey washover in all three cores.

There are several possible explanations of how the four known washover beds in the marsh cores can be represented by up to nine washover beds identified in the lake cores: 1) bioturbation (e.g., burrowing) may have displaced sediment from one washover bed, creating two or more apparent washover beds; 2) slight variations in elemental composition within a single washover bed may have resulted in different parts of the bed being placed into different clusters, giving the appearance of two or more washover beds; 3) some of the washover beds identified by cluster analysis may be from smaller storms that did not leave visible sandy layers within the marsh cores, do not have pronounced LOI profiles, but do have elemental compositions that match the elemental "fingerprints" used in clustering; 4) washover beds of

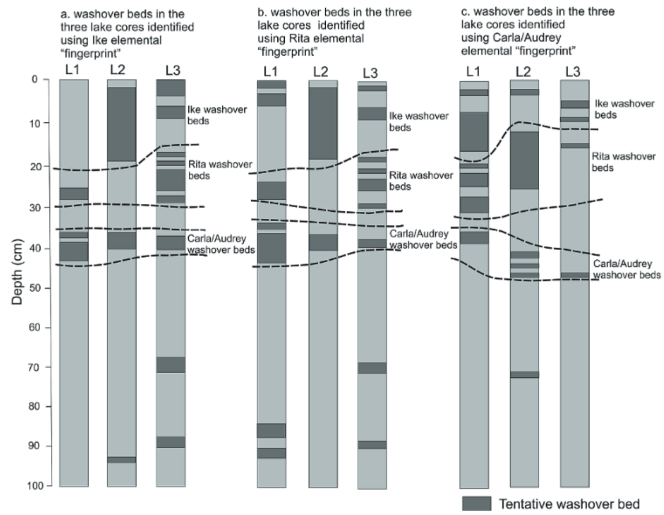

Fig. 6. Sediment layers in lake cores L1, L2 and L3 matching elemental compositions of a. washover beds of Hurricanes Ike, b. washover beds of Hurricane Rita and c. washover beds of Hurricanes Carla/Audrey. Dashed lines separate suspected washover beds in the shallow parts of cores attributed to Hurricane Ike, at intermediate depth attributed to Hurricane Rita, and deeper washover beds attributed to Hurricanes Carla/Audrey. Additional tentative washover beds in the lower halves of cores are of unknown origin.

Hurricanes Carla and Audrey may be mixed together and identified as a single washover bed, or they may be separated by marsh sediments and identified as two distinct washover beds.

Fig. 6 contains some notable omissions: no Hurricane Ike washover bed was detected in core L1 using the Ike elemental "fingerprint"; a Hurricane Rita washover bed was not found in core L2 using both the Ike and Rita elemental "fingerprints"; no Hurricane Rita washover bed was found in core L3 using the Carla/Audrey elemental "fingerprint." In each case, it is likely that these "missing" washover beds are present, but were not detected by the clustering technique, presumably because their elemental compositions did not sufficiently match a washover bed elemental "fingerprint".

Fig. 6 also contains certain consistencies that support the interpretation of washover beds within the cores. Firstly, there is a sharp contrast in the number of washover beds detected in the upper half of all three cores compared to the lower half. This provides a degree of confidence that the clustering technique is not generating "false hits"; many washover beds are detected in the upper half of cores where washover beds from Hurricanes Ike, Rita, Carla and Audrey are expected. In the lower half of the cores, two additional washover beds are detected, at a depth of about 70 cm (in cores L2 and L3) and at a depth of about 90 cm (in cores L1, L2 and L3) (Fig. 6). The bed at 70 cm depth appears to correlate with a visible sand layer and a spike in sand content in cores M2 and M3 at a depth of about 50 cm[1] (Fig. 4). These beds are most likely older washover beds deposited by unknown hurricanes or large storms. Secondly, washover beds attributed to Hurricanes Carla/Audrey are consistent in occurrence and stratigraphic position; these washover beds are found in all three lake cores using all three elemental "fingerprints." These washover beds occur at about 40 cm depth, which is comparable to the depth of the Carla/Audrey washover beds in the marsh cores (~33–46[1] cm depth) (Fig. 4).

The results suggest that as many as nine washover beds are present in the lake cores (Fig. 6). Given the known thicknesses and ages of washover layers in the marsh cores and assuming that the bases of the Carla/Audrey washover deposits are correctly identified in the lake cores, provides a means to evaluate i) periods of heightened or diminished overwash activity ii) the thickess of sediment deposited at each core site since 1957 (landfall of Hurricane Audrey), iii) the combined thickness of washover layers in each core since 1957, iv) the contribution of washover to overall sedimentation and v) the average sedimentation rate at each core site for the 63-year period 1957 to 2020. Because the lake cores were analyzed using three different elemental "fingerprints", results of the analyses were averaged for each core; this information is presented in Table 2.

Table 2
Washover percentages and sedimentation rates for lake and marsh cores.

	L1	L2	L3	M1[b]	M2[b]	M3[b]
Depth to base of Audrey layer (cm)[a]	41	42	42	49	39	34
Washover combined thickness (cm)[a]	17	21	12	25	22	11
Washover %[a]	41	50	29	51	56	32
Sedimentation rate 1957–2020 (cm/yr)	0.65	0.67	0.67	0.78	0.62	0.54

[a] Depth to base of Audrey layer, washover combined thickness and washover % found using elemental fingerprints of hurricanes Ike, Rita and Carla/Audrey, averaged for cores L1-L3.
[b] Depths/rates for marsh cores corrected for compaction.

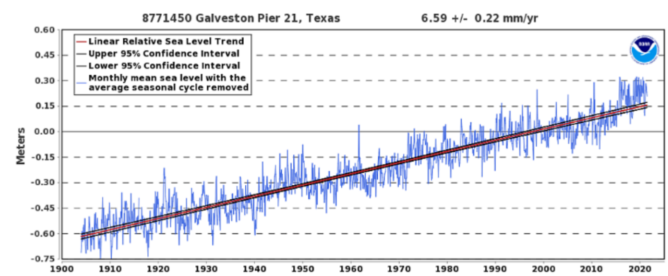

Fig. 7. Relative Mean Monthly Sea Level Trend Galveston Pier 21, Texas, 1904–2020.

Stratigraphically, there is a clear disparity in the distribution of washover layers in the lake cores, with the majority of layers being present in the upper half of the cores (Fig. 6). The reason for this apparent heightening of overwash activity after 1957 is unknown; it may be that fewer large storms impacted the study area in the period prior to Hurricane Audrey. It is also possible that natural or artificial changes in site conditions, for example sea-level rise or lowering of foredunes, have increased the magnitude and frequency of washover sedimentation in the lake.

The thickness of sediment deposited at each core site since 1957 is fairly consistent, averaging 41 cm and varying from 34 to 49 cm. The combined thickness of washover layers within each core results in contributions of washover to overall sedimentation of 29 to 56%. This finding underscores the significance of hurricane-related sedimentation to marsh and lake aggradation; in cores L2, M1 and M2, the percentage contribution of washover is at or above 50%. Overall sedimentation rates between 1957 and 2020 are also fairly consistent, ranging from 0.54 to 0.78 cm/yr and averaging 0.66 cm/yr (Table 2).

There is close agreement between sedimentation rates in the lake and marsh cores, and the local rate of sea-level rise, as measured at Galveston Pier 21, Texas, 80 km west of the study area (Fig. 7; NOAA, 2021). Sedimentation rates in the lake cores, ranging from 0.65 to 0.67 cm/yr closely match local sea-level rise of 0.66 cm/yr; sedimentation in the marsh cores ranges from 0.54 to 0.78 cm/yr and averages 0.65 cm/yr (Table 2). These results suggest that sedimentation in the lake and marsh may be driven by, and keep pace with, local sea-level rise. Rising sea-level would presumably promote greater frequency and magnitude of both flooding and storm overwash, resulting in increased organic and inorganic sedimentation. This finding aligns with other recent studies of

[1] Depths increased to account for compaction.

marsh accretion that show many marshes are able to keep pace with accelerated sea-level rise given sufficient sediment supply (Kirwan et al., 2016).

5. Conclusions

The XRF analysis of the four known washover beds in the marsh cores suggest that, at this site at least, there is no "universal" washover elemental composition, but different elemental compositions for parts of the same washover deposit and for washover beds of different hurricanes. There was enough elemental consistency within individual washover beds to enable "elemental fingerprints" to be constructed and to be used to tentatively identify many washover beds in the lake cores. Based on the stratigraphic relationships of washover beds in the nearby marsh cores, washover beds in the lake cores could be tentatively attributed to the four known hurricanes. Results are promising, although some washover beds were not detected by the clustering technique and some lake cores appear to have more than four washover beds, presumably because of bioturbation, identification by the clustering technique of two or more washover beds in a single washover deposit and washover beds from smaller storms. Consistency in the occurrence and stratigraphic position of the Carla/Audrey washover beds in all three lake cores provides a degree of confidence that the clustering technique is accurately detecting washover sediments. Tentative identification of washover beds in the lake and marsh cores suggest i) a period of heightened washover activity after Hurricane Audrey (1957), ii) washover contributed 29 to 56% of sedimentation between 1957 and 2020, iii) sedimentation rates in the lake and marsh are in close agreement with, and may be driven by, local sea-level rise. The XRF technique is a promising tool for improving understanding of sedimentation sources, pathways and rates in coastal lakes where washover beds may be indistinguishable from lake sediments based on microfossil, LOI and textural characteristics.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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