The Effects of Hurricanes Katrina and Rita on the Seabed of the Louisiana Shelf

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ABSTRACT
The legacy of hurricanes Katrina and Rita on land has been one of human devastation and long-term damage to the infrastructure of communities along the northern Gulf of Mexico. In addition, these hurricanes had major impacts on offshore regions of the shelf and slope. A multi-institution, rapid-response effort investigated the immediate effects of the storms on the seabed off the Louisiana coast. These studies revealed intense reworking of surface sediment layers during the storm passage and re-deposition of materials following the hurricanes over a broad area of the shelf and slope. The pattern of deposition varied significantly along the region between the Mississippi and Atchafalaya rivers, depending on both the characteristic of the shelf and the paths of the storms. Geochemical tracers indicate the origin of the materials in the post-hurricane layers was predominantly local sediments mobilized by the intense wave activity during the storms. The combined impact of the hurricanes was a massive disturbance of benthic communities throughout the region, including marked erosion of the seabed in the shallower regions of the shelf and elevated deposition of sediments in the deeper regions. The total amounts of sediment, carbon and nitrogen re-deposited following the storm far exceeded the combined annual inputs of these materials by the Mississippi/Atchafalaya Rivers. The characterization of these storm deposits provides an opportunity to investigate the history of hurricane activity in the recent past based on the sedimentary record preserved in this region.

HURRICANES KATRINA AND RITA

Hurricane Katrina originated as a tropical storm on August 24, 2006 over the central Bahamas, becoming a Category 1 hurricane on August 25 as it made initial landfall on the southeastern coast of Florida. After crossing the Florida peninsula on a westward path, Katrina quickly regained hurricane status, intensifying into Category 3 status and doubling in size on August 27, 2006. By August 28, Katrina had become a Category 5 storm with peak winds of over 280 Km/h. Early on August 29, Katrina started to move northward, making landfall on August 29, 2006 as a large Category 3 hurricane near Buras, Louisiana. Maximum sustained winds measured during landfall reached 140 Km/h at the atmospheric station located at Grand Isle, LA, with wind gusts of up to 200 Km/h. The station at Southwest Pass, LA, measured sustained winds of 130 Km/h.

Storm surge measurements during the peak of the storm were compromised due to the widespread failure of tide gauges. However, high mark observations indicate the maximum storm surge (7-9 m) was measured along the Mississippi Coast near St. Louis Bay, with lower surges (3-6 m) measured along the eastern Louisiana coast and the New Orleans area. Katrina generated large, northward-propagating swells, with significant wave height measurements that ranged from 9 to 17 m at a buoy 64 nautical miles south of Dauphin Island, Alabama. Storm-related precipitation ranged from 20 to 30 cm of rain along a swath that extended from southwestern Mississippi to eastern Louisiana. The economic and environmental damages associated with Katrina have been widespread, accounting for over $40 billion of insured losses, with preliminary estimates of total damage over twice that figure (summarized from Knabb et al., 2006a).

Just as the region was starting to recuperate from the effects of Katrina, Hurricane Rita moved west-northwest over the Turks and Caicos and the Southern Bahamas on September 18, 2006. Rita became a tropical storm on September 19, becoming a hurricane on September 20 as it approached the Florida Keys. As Rita entered the Gulf of Mexico, its strength increased, quickly intensifying to a Category 5 hurricane by September 22 with estimated peak winds of 290 Km/h. As it moved west-northwest, Rita weakened to Category 3 status up to the time of landfall on the morning of September 24, 2006. Rita came ashore in western Louisiana near the Louisiana/Texas border, just west of Johnson's Bayou (LA) and east of Sabine Pass (TX). Rita brought 185 Km/h winds to the region near the landfall area, while 130 Km/h winds were measured over wider areas of Texas and Louisiana.

A significant storm surge, ranging from 2 to 5 m was observed in southwestern Louisiana, as far east as Vermillion (LA). Rita also produced smaller storm surge (1-2 m) in regions of southeastern Louisiana that were highly impacted by Hurricane Katrina a month earlier. Storm-related precipitation amounted to 13 to 23 cm in many regions of Mississippi, Louisiana and eastern Texas. Storm-associated damage to insured property was estimated to be over $5 billion, with total damage estimates accounting for about $10 billion (summarized from Knabb et al., 2006b).

RAPID RESPONSE EFFORT

In the days following the landfall of Katrina, plans were drawn to mount a rapid response field effort to investigate the effects of the hur-

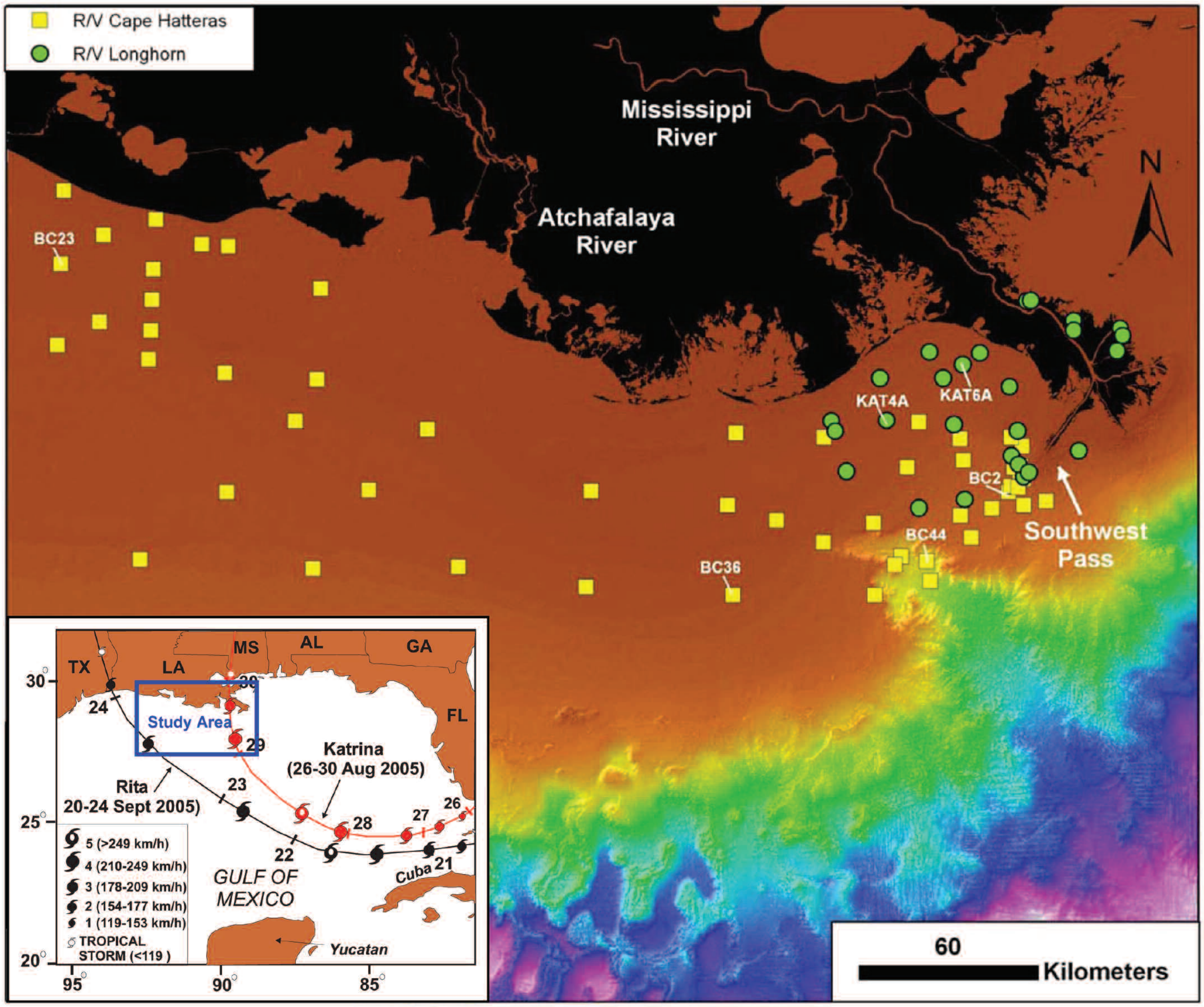

Figure 1. Map of the study area showing the location of the coring stations along the Louisiana margin. The insert shows the path and strength of Hurricanes Katrina and Rita.

ricane on the continental shelf environment. Two ships, the R/V Cape Hatteras and R/V Longhorn, were identified as being available with funding from the National Science Foundation and the Office of Naval Research, respectively. Cruise plans had to be altered in several occasions, when Hurricane Ophelia affected the departure of the R/V Cape Hatteras from the South Atlantic Bight and when Hurricane Rita came into the Gulf of Mexico. Ports of departure had to be changed in the aftermath of Hurricane Rita because of major coastal flooding in all of western Louisiana including LUMCON's facilities at Cocodrie (LA) from which the research cruises were originally scheduled to depart.

On September 26, 2005, scientific teams from East Carolina University (Corbett, Walsh and Mallison) and Oregon State University (Goni) boarded the R/V Cape Hatteras in Pensacola (FL), the only available major port open in the central part of the Gulf. Researchers from Tulane University (Allison), Texas A&M (Dellapenna) and University of Massachusetts, Amherst (Gordon), boarded the R/V Longhorn at Galveston on Sept 29. Investigators aboard the R/V Cape Hatteras focused their efforts on the shelf and slope off the Mississippi Southwest Pass, along the mouth of the Mississippi Canyon and west towards the Atchafalaya River shelf region offshore from the Chenier Plain (Fig. 1). The research group aboard the R/V Longhorn sampled and collected data from the inner regions of the Mississippi Bight and coastal marshes on the west and east of the bird foot delta.

A multi-beam swath bathymetry system was installed aboard the R/V Hatteras and used to map the seabed off Southwest Pass to investigate the slump morphology of this region (Walsh et al., 2006). A chirp sub-bottom profiling system was towed from the R/V Longhorn and used to map the subsurface seabed within the Mississippi Bight. In addition, both ships were fitted with various coring equipment, box corers, a multi-corer and Kasten corers that were used to sample the seabed at over 80 different locations (Fig. 1). Once retrieved, sediment cores were X-rayed, described, and sub-sampled for a variety of purposes.

Sediment samples were collected to measure the activities of natural radionuclides (^{210}Pb, ^{7}Be, and ^{234}Th), porosity, grain size and various geochemical parameters. These latter included

Table 1. Estimates of total mass accumulation of sediment, organic carbon and nitrogen on the seabed due to the combined Rita and Katrina events in contrast to annual inputs by rivers and regional primary production.

	Sediment	Organic Carbon	Nitrogen
Rita/Katrina Accumulations (g)	$1.16\times10^{15} \pm 1.56\times10^{14}$	$1.36\times10^{13} \pm 2.46\times10^{12}$	$1.56\times10^{12} \pm 2.5\times10^{11}$
Annual Inputs (g/y)			
Combined Mississpi/Atchafalaya Rivers	2.16×10^{14}	3.62×10^{12}	3.96×10^{11}
Regional Net Primary Production		$1.05\times10^{13} \pm 3.82\times10^{12}$	$1.74\times10^{12} \pm 6.36\times10^{11}$
Non-Hurricane Accumulations (g/y)	1.18×10^{14}	1.17×10^{12}	1.40×10^{11}

Seabed accumulation rates account for the porosity values measured in storm and non-storm deposits.
Estimates of annual inputs (river discharge and primary productivity) and of non-hurricane accumulations are from Gordon and Goni, 2004.

weight percent inorganic and organic carbon content (%IC and %OC, respectively), organic carbon:nitrogen ratios (OC:N) and the stable isotopic compositions of organic carbon and nitrogen ($\delta^{13}C$ and $\delta^{15}N$, respectively). Radiocarbon compositions were measured in selected samples to evaluate the age of the organic matter in these deposits. Combined, these compositions were used to evaluate the provenance and composition of sediments and associated organic materials deposited after the storms in order to assess the overall effects of the two hurricanes.

HURRICANE-CAUSED EROSION AND DEPOSITION

Although incomplete due to the failure of many instruments, wind, wave and storm surge records all indicate extreme conditions on the shelf during the heights of the storms. Under these conditions, massive mobilization of large amount of sediments took place, followed by the deposition of storm layers throughout the study area. Based on radionuclide profiles and careful examination of X-rays, we were able to estimate the thickness of the storm layers, which are illustrated in Figure 2. In several cores, estimates of seabed erosion are possible due to the absence of post-storm deposition and the existence of pre-hurricane cores (Fig. 3, KAT6A). These estimates indicate that up to 8 cm of sediment were eroded from the seabed as a result of both storms. However, these are conservative estimates since storm incision was impossible to quantify due to the lack of markers within the sediment column at most sites. The sites where there was net erosion but no deposition were all located in the inner Mississippi Bight region and most likely resulted from the passage of Hurricane Katrina across the region. Wave energy was likely to have remained high for a long period in this region and perhaps there was no direct source of re-suspended material available to be deposited in the days following storm passage.

Most sites cored yielded sediments that upon X-ray and radionuclide analyses showed clear storm layers (e.g., Corbett et al., submitted). A majority of the sites in the eastern part of the study area clearly showed two storm layers, the deeper one associated with Katrina and the surface unit being the result of Rita (Fig. 2). In contrast, all sites off the Atchafalaya River mouth showed only one distinct storm layer, which we assigned to Hurricane Rita. In both cases the pattern of hurricane deposits is the result of interactions between storm waves and the seabed. We believe that at depths shallower than about 20 meters, both hurricanes caused re-suspension of surface sediments followed by deposition after energetic conditions subsided. In the shallow regions of the shelf, including those located within the Mississippi Bight (Fig. 3, KAT4A) and along the Atchafalaya Shelf (Fig. 3, BC23), wave conditions during Rita were high enough to completely remove the sediments deposited following Katrina. In fact, several of these cores display a clear erosional surface associated with this process (Fig. 3, BC23). In these regions only a single storm layer associated with Hurricane Rita survived.

In the deeper region of the Mississippi and Terrebonne shelf (depths >30 m) two storm deposits are evident (Fig. 3, BC2). In a few cores off the Mississippi Delta, we can in fact detect three storm layers. ^{210}Pb profiles indicate the third deepest layer was initially

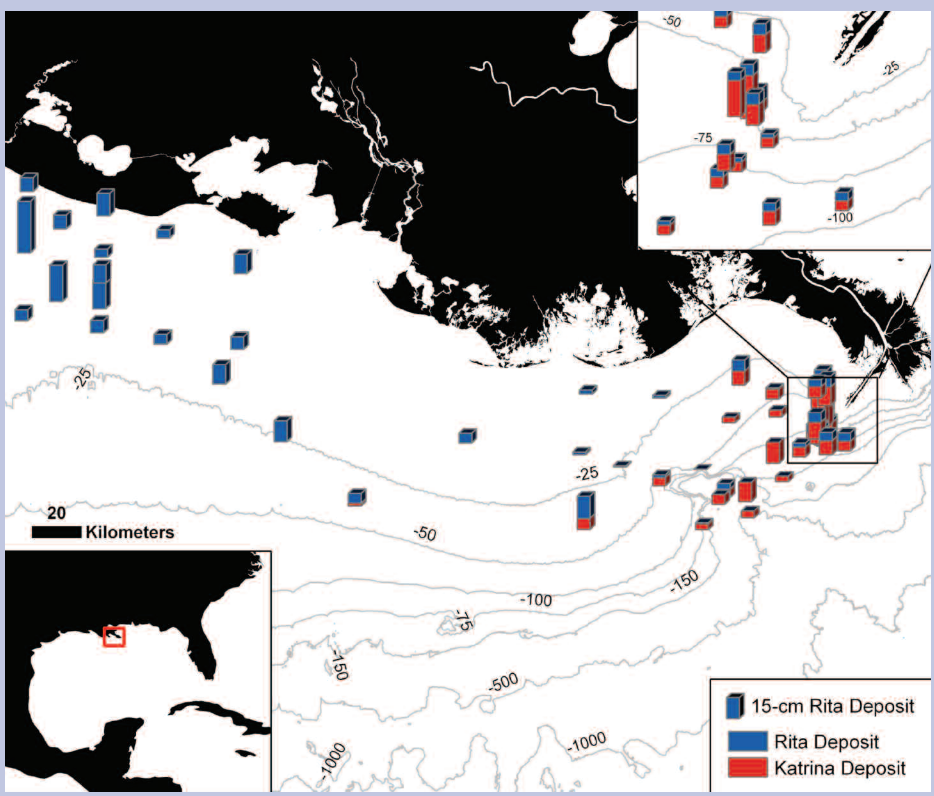

Figure 2. Map illustrating the thickness of sediment deposits associated with Hurricanes Katrina and Rita.

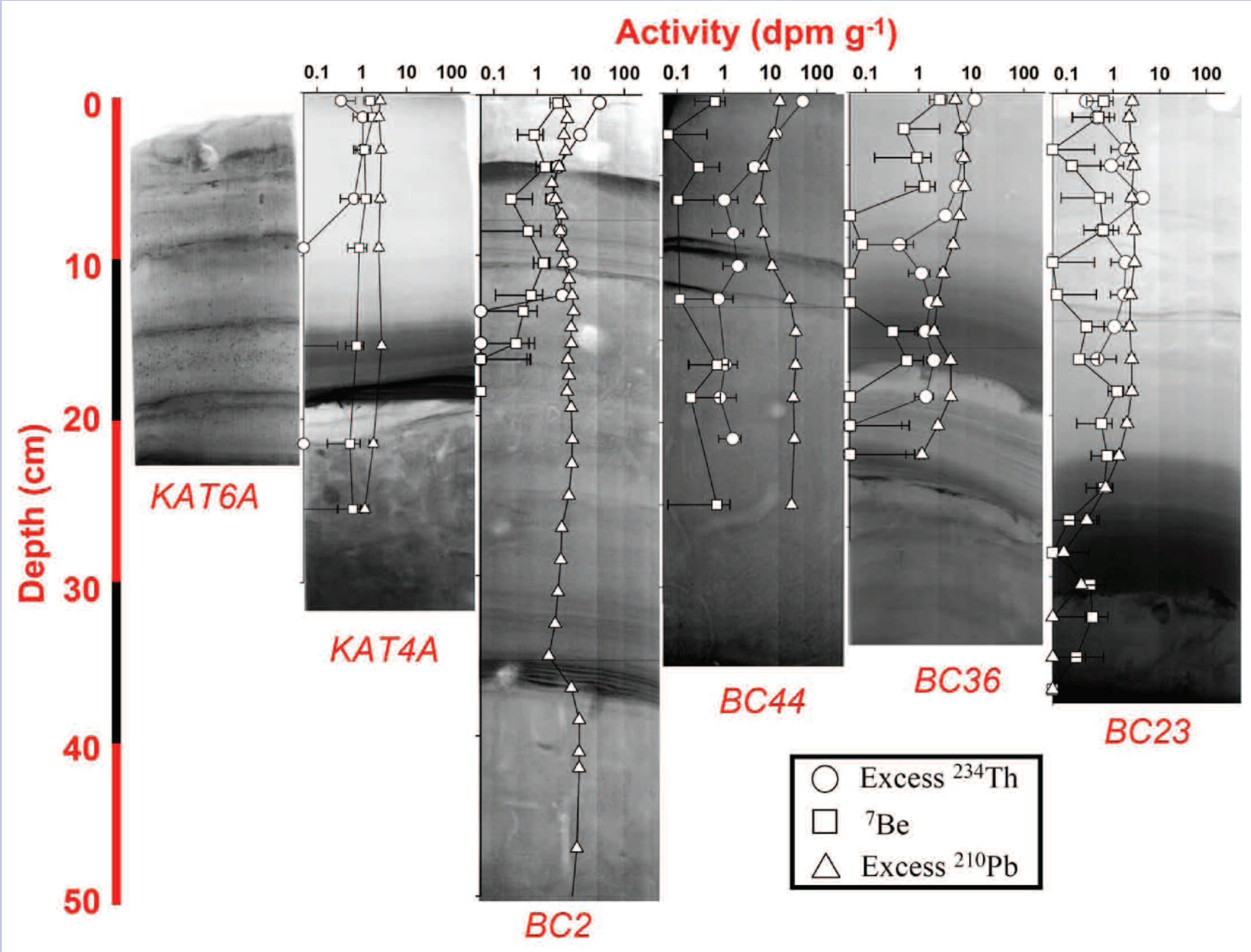

Figure 3. X-radiographs of representative cores from sites along the Louisiana margin collected after Hurricanes Katrina and Rita. Included in the graphs are available data on the radionuclide inventories measured. Profiles of excess ^{234}Th, ^{7}Be and excess ^{210}Pb are included.

deposited after Hurricane Ivan in 2004 (Corbett et al., 2006) and was left intact after the passage of Katrina and Rita. These deposits show no evidence for erosional surfaces below the base of the storm layers, indicating wave energy at these depths was not high enough to resuspend materials from the seabed. In contrast, we found no evidence for storm deposits in the deeper regions of the shelf off the Atchafalaya River, suggesting materials resuspended during the storms were not transported across shelf in this part of the Louisiana shelf. The broad, flat bathymetry in this region of the shelf likely limited cross-shelf transport through gravity flows. In contrast, the steep bathymetry off the Mississippi River shelf region probably facilitated cross-shelf gravity flows, which is the process most likely responsible for the storm deposits found in this region (e.g., Allison et al., 2005).

COMPOSITION OF HURRICANE DEPOSITS

Short-term (^{7}Be and ^{234}Th) and long-term (^{210}Pb) radionuclide inventories are presented in Figure 3 and are discussed in detail elsewhere (e.g., Walsh et al., 2006; Corbett et al., submitted). Briefly, these data show elevated ^{234}Th activities and lower but measurable ^{7}Be activities in both Rita and Katrina deposits. The low ^{7}Be/^{234}Th ratios of the post-hurricane deposits are consistent with a predominant resuspension source, which results in the exposure of sediment particles to seawater and promotes the adsorption of ^{234}Th prior to deposition (Corbett et al., 2004). The low ^{7}Be activities are consistent with a minor input of fresh river sediments, which are typically enriched in this cosmogenic isotope due to high-drainage basin to estuarine surface area (Baskaran et al., 1997; Sommerfield et al., 1999). This interpretation is supported by the fact that both Rita and Katrina caused minor increases in the discharge of both the Mississippi and Atchafalaya rivers (Corbett et al., submitted), which at this time of the year are at their lowest stage. Furthermore, the elemental (OC:N) and stable carbon isotopic (δ^{13}C) ratios of surface sediments deposited following the passage of both hurricanes show remarkable agreement with the compositions measured in surface sediments from the region prior to the storms (Fig. 4). Again, these findings support our contention that the source of the hurricane deposits was locally resuspended sediment. There is little evidence for a significant input of allochthonous sediment and organic matter, such as might be exported from the erosion of coastal marshes and bayous.

The geochemical profiles of two representative cores are illustrated in Figure 5. Other core profiles have been discussed in previous

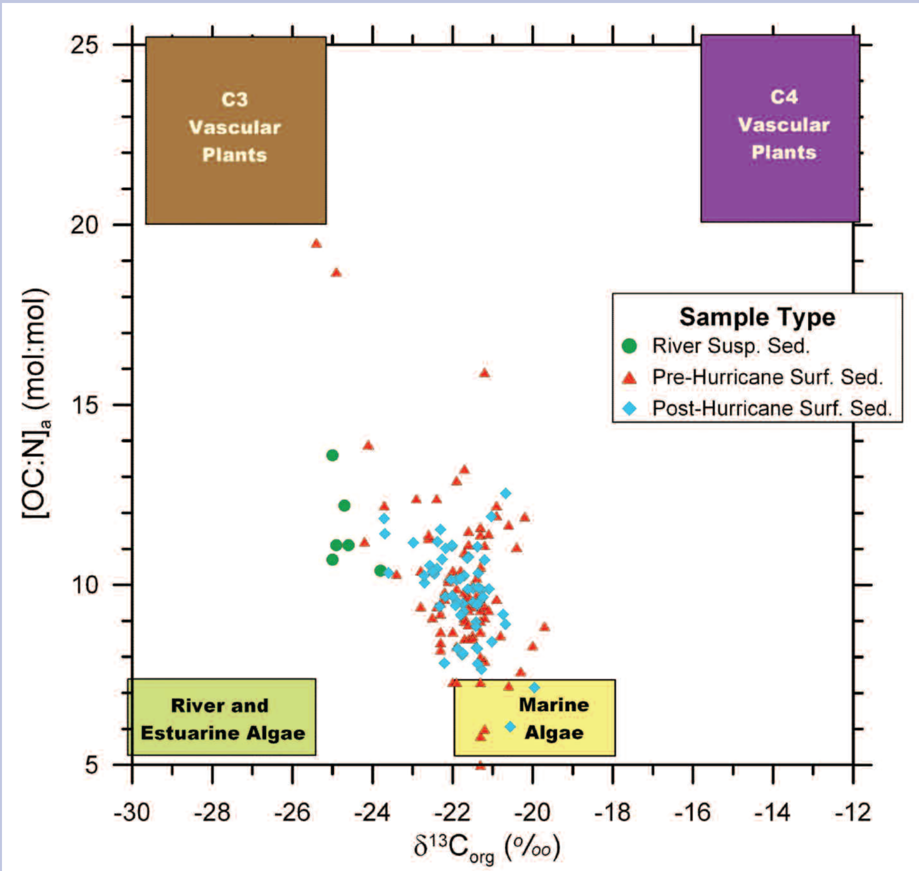

Figure 4. Plot of the stable isotopic composition of organic carbon ($d^{13}C_{org}$) versus the atomic organic carbon:nitrogen ratio ($[OC:N]_a$) of pre- and post-hurricane surface sediments from the Louisiana margin. Included in this graph are compositions of suspended sediments collected from the mouths of the Atchafalaya and Mississippi rivers prior to the hurricanes (Gordon and Goni, 2003), the compositions of surface sediments collected from the Louisiana margin prior to the hurricanes (Goni et al., 1998; Gordon et al., 2001; Gordon and Goni, 2004), along with the composition of surface sediments collected after the hurricanes (this study).

publications (e.g., Corbett et al., 2006); but in general they all share common features. For example, the Hurricane Rita deposits found on the top of BC36 and BC23 cores display fining up sequences with well developed basal layers. These latter layers, which are characterized by low %OC values, low [OC:N] ratios and high [IC:OC] ratios, were deposited during the waning periods of the storm when wave energy subsided. They are enriched in coarse debris, including shell fragments with high carbonate content. The finer sediments deposited on top of the coarser sediments, on the other hand, are much more clay rich. These finer deposits are quite uniform and display relatively high %OC and [OC:N] ratios and lower [IC:OC] ratios.

The Katrina deposit in BC36 shows compositions that suggest part of the deposit may have been eroded during Rita's passage. For example, x-rays indicate relatively coarse material, which is consistent with the relatively low %OC values, low [OC:N] ratios and high [IC:OC] ratios. In that respect, the Katrina deposit at this time resembles more closely the basal layer of the Rita deposit directly above than the fine sediments in place near the sediment water interface. At its height, Rita probably led to bottom shear stresses that exceeded the levels necessary to resuspend seabed materials at 30 m water depth.

It is interesting to note the chemical differences in the Rita deposits between BC36 and BC23. The latter displays much more uniform compositions, lower [OC:N] ratios and enriched $\delta^{13}C$ values (particularly in the top 10 cm). In addition, the Rita layer in BC23 shows two distinct sub-layers, divided by a lense of fine sand (e.g. Fig 3), which suggest there were two post depositional events in this region of the Louisiana Shelf. The differences in %OC, [OC:N], [IC:OC] and $\delta^{13}C$ values all suggest differences in the specific sources of materials deposited (e.g., Gordon and Goni, 2004). Overall, however, the compositions of these sediments are remarkably similar to those of pre-storm deposits (Fig. 4), indicating the major source of sediment and POC in the storm layers is local materials that were resuspended and redistributed following the passage of the hurricanes (Corbett et al., 2006).

REGIONAL IMPACT OF HURRICANES

The massive resuspension and re-deposition of sediments caused major disruption of benthic ecosystems. In shallower regions, large seabed incision was followed by deposition of highly sorted materials, leading to significant disruption of benthic biota. In deeper regions, the hurricanes led to the deposition of several cm-thick layers of sediment and associated materials in regions where long-term accumulation rates are typically low (a few mm per year; Goni and Gordon, 2004). Hence, hurricane-induced deposition of sediment and organic matter in these areas was orders of magnitude higher than the steady-state annual accumulation rates determined prior to the storms (e.g. Corbett et al., submitted). In these environments, stochastic events such as these hurricanes may indeed dominate input fluxes and be responsible for the bulk of clinoform growth and organic matter burial (e.g., Goni et al., 2006).

Overall, the total storm-induced accumulation of sediments throughout the study area was five times greater the annual supply of sediment by the combined Mississippi and Atchafalaya rivers and is 10 times greater than the annual, long-term accumulation during non-storm periods (Table 1). In the case of organic carbon, total accumulation after both storms is the same order of magnitude as the combined annual inputs from the Mississippi/Atchafalaya River and the estimated primary productivity over this region of the shelf. The total storm accumulation of OC on the seabed is one order of magnitude higher than the non-storm estimate. A similar picture arises in the case of nitrogen (Table 1). All of these calculations illustrate the massive impact of the 2005 storms on the biogeochemistry of the seabed throughout a larger region of the northern Gulf of Mexico.

FUTURE WORK

An area of on-going and future research is the investigation of the fate of the hurricane deposits. Bioturbation and physical mixing are likely to alter and erase the biogeochemical and sedimentological signatures of these deposits, especially those located in the shallower regions of the shelf. On the other hand, as illustrated by Fig. 3, BC2, storm deposits appear to be preserved in deeper sites. Hence,

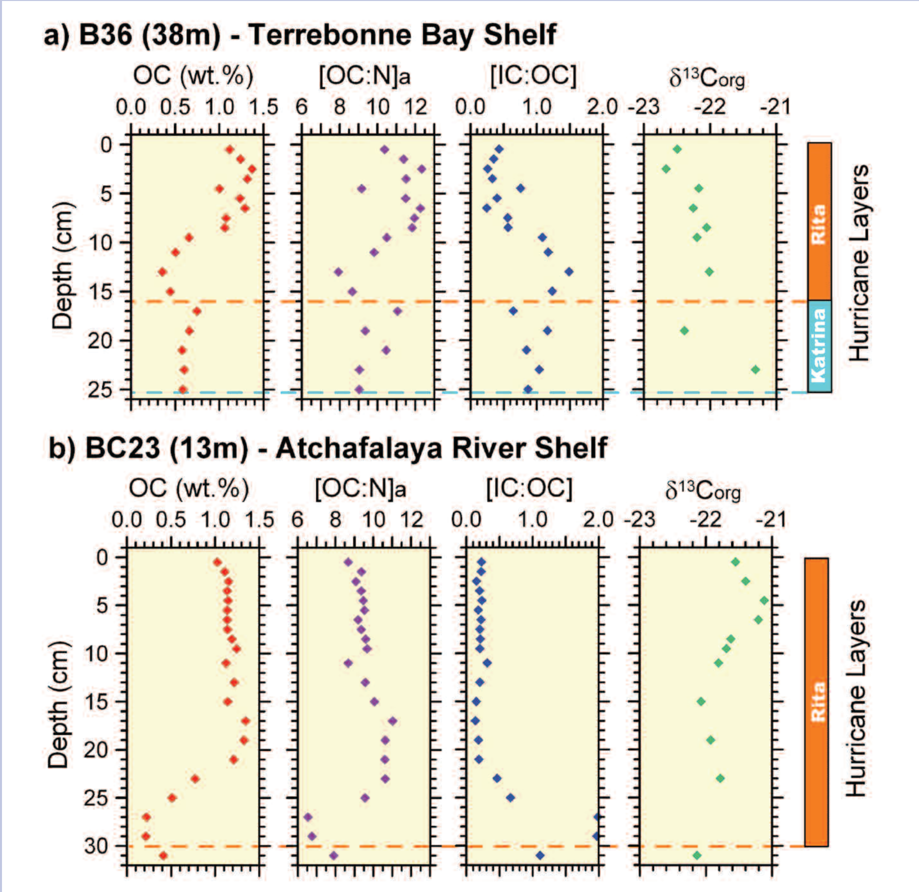

***Figure 5.** Profiles of several geochemical properties, including weight percent organic carbon content (%OC), atomic organic carbon:nitrogen ratios ($[OC:N]_a$), inorganic carbon:organic carbon ratios ([IC:OC]) and stable isotopic compositions of organic carbon ($d^{13}C_{org}$), of two representative cores from the eastern (Terrebonne Bay Shelf) and western (Atchafalaya River Shelf) regions of the study area. The depths of the hurricane layers, which were determined by visual inspection of the x-rays and the distribution of ^{7}Be and ^{234}Th, are indicated with the bars at the right of the profiles.*

it is possible that deeper regions of the shelf and slope may contain long-term records of hurricane deposition. The sedimentological and geochemical compositions of the Ivan, Katrina and Rita deposits provide us with information needed to identify similar hurricane-derived layers in the sedimentary record. However, as illustrated by differences among the various hurricane deposits (e.g., Fig. 3), it will be very challenging to use these records to reconstruct hurricane intensity. For example, although Katrina was a more intense hurricane that came ashore much closer to the core site than Ivan, the latter produced a much thicker storm deposit (Corbett et al., 2006). We speculate that while wave energy off Southwest Pass during Katrina greatly exceeded conditions during Ivan, there was much more unconsolidated sediment available for resuspension in 2004, when Ivan struck the region, than in 2005. It is likely that periods of high hurricane frequency may have resulted in multiple, smaller storm deposits, whereas singularly thick deposits may characterize periods of infrequent storms.

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