Impact of Hurricane Katrina (2005) on shelf organic carbon burial and deltaic evolution

Mead A. Allison,[1] Timothy M. Dellapenna,[2] Elizabeth S. Gordon,[3] Siddhartha Mitra,[4] and Steven T. Petsch[5]

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[1] Sediment cores from the continental shelf adjacent to the Mississippi River delta immediately after the passage of Hurricane Katrina were used to examine the magnitude, and implications for the carbon budget, of sediment and particulate organic carbon (POC) remobilized by the storm on the river-dominated continental shelf. POC was sourced from incision of the innermost continental shelf (<25 m water depth) and from surge ebb advection from adjacent wetlands and shallow estuaries, and was re-deposited in deeper water on the shelf. This pulse of young (<1,600 yBP) labile POC, mixed with relict (>5000 yBP) POC eroded from the seafloor, has major implications for the remineralization versus burial of POC in deltas. The scale of erosional deflation of the shelf in water depths beyond seasonal wave-current conditions suggests that, over millennia, tropical cyclones may be responsible for partly removing prodeltaic strata from the geologic record in low-to-mid latitude deltas. **Citation:** Allison, M. A., T. M. Dellapenna, E. S. Gordon, S. Mitra, and S. T. Petsch (2010), Impact of Hurricane Katrina (2005) on shelf organic carbon burial and deltaic evolution, *Geophys. Res. Lett.*, *37*, L21605, doi:10.1029/2010GL044547.

1. Introduction

[2] Hurricane Katrina traversed the shelf and coast of south Louisiana adjacent to the Mississippi River delta on August 29, 2005 with sustained winds in excess of 110 knots (56.6 m/s) and storm surges in the delta of up to 4–5 m [*Knabb et al.*, 2006]. This caused huge land losses from the fragile deltaic coastal wetlands [*Barras*, 2006], and conversely, net sediment accretion on some marsh areas not excavated by the storm [*Turner et al.*, 2006]. These studies suggest the possibility of large-scale exchange of sediment and particulate organic carbon (POC) between wetland, estuarine, and offshore areas of deltas impacted by tropical cyclones.

[3] Rivers supply as much as 1 Gt total carbon to the world's oceans, and as much as 85% of the carbon burial in continental margins takes place on these river-dominated shelves [*Berner*, 1982; *Bianchi and Allison*, 2009]. The Mississippi River is one of the world's 25 largest rivers, that together account for approximately 40% of the fluvial sediments and 50% of the freshwater entering the ocean [*Meade*, 1996; *Vorosmarty et al.*, 2000]. A number of these low and mid-latitude systems, including the Mississippi, are subjected to tropical cyclones. We hypothesize that these events resuspend large amounts of sediment from continental shelf depocenters, which expose particulate and dissolved OC to remineralization (affecting carbon burial rates), homogenize OC from labile and more recalcitrant sources, and re-introduce nutrients to coastal food webs. We also hypothesize that these events have a lasting impact on deltaic evolution by incising older sediment deposits as well as the modern depocenter(s). In the Mississippi delta, lobe-switching on 10^2–10^3 y timescales in the late Holocene has created overlapping, 10–200-m-thick lobe deposits which are conceptually modeled as evolving by compaction-driven relative sea level rise and shoreface transgression by wave attack [*Penland et al.*, 1988; *Törnqvist et al.*, 2008]. We hypothesize that the wave and surge energy of tropical storms may extend this incision to shelf depths, playing a major role in preservation of these lobes. The objective of this paper is to test these hypotheses by examining the Katrina event and its impact on carbon burial/remineralization and geologic preservation of deltaic lobe deposits.

2. Materials and Methods

[4] Field and laboratory methods are outlined in the auxiliary material methods section.[1]

3. Seabed Response and Sediment Mass Fluxes

[5] During a rapid response cruise conducted on Oct. 1–6, 2005, 19 cores (Figure 1) were collected from the continental shelf. In addition to being directly in Katrina's path, the study area was selected because it is the largest modern Mississippi sediment accumulation depocenter [*Corbett et al.*, 2006]. X-radiographs from the cores exhibit a storm seabed response that can be divided into four categories based on A) the presence or absence of an irregular, basal erosional surface that marks the transition from pre-storm and Katrina event layer surficial deposits and B) the presence or absence of a fining-upward event layer attributable to the storm. The Katrina event layer is attributed based on the presence of the particle-reactive, short-period radiotracer ^{7}Be (half life = 53 days), which tends to be high in activity on river-derived particulates, and, secondarily, on the fining upward stratig-

[1] Institute for Geophysics, University of Texas at Austin, Austin, Texas, USA.
[2] Department of Marine Sciences, Texas A&M University at Galveston, Galveston, Texas, USA.
[3] Department of Geo/Physical Sciences, Fitchburg State College, Fitchburg, Massachusetts, USA.
[4] Department of Geological Sciences, East Carolina University, Greenville, North Carolina, USA.
[5] Department of Geosciences, University of Massachusetts at Amherst, Amherst, Massachusetts, USA.

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL044547.

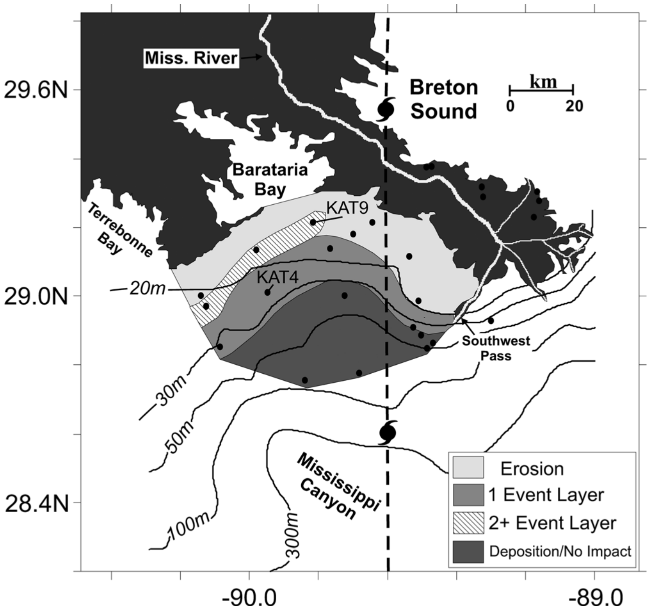

Figure 1. Map of the core sites (offshore and marsh) on the continental shelf west of the Mississippi River mouth and the path of the eye of Hurricane Katrina in August 2005. The zones of event layer character resulting from Katrina's erosion and deposition are discussed in the text. The two sites where downcore organic carbon analyses were conducted are identified (KAT4, KAT9).

raphy [*Olsen et al.*, 1986; *Allison et al.*, 2005; *Keen et al.*, 2006]. This event layer is interpreted as being a result of seabed erosional deflation during the period of maximum wave heights and onshore, surge-induced currents. The waning phase would be marked by re-deposition of particles (that fined with gradual energy reduction) suspended by the storm, and runoff of additional particles from the land surface, associated with an ebbing surge (offshore vector). Event layer thicknesses in X-radiograph and depth of ^{7}Be penetration are reported for each station in Table S1 of the auxiliary material.

[6] The zonations in Figure 1 strongly correlate with water depth. In water depths of less than about 25 m, box cores showed no event layer preservation and an erosional sediment surface. These cores were uniformly composed of well consolidated (porosity 50–60%) and burrowed muds with a thin (<2 cm) shelly sand veneer. At three of these sites (KAT 6,7,14), we were able to compare box core X-radiographs with those collected at the same GPS location in May 2005 by a NOAA-funded study (S. DiMarco, lead PI). Using matching subbottom stratigraphy, seafloor deflations were 2, 3, and 8 cm, respectively, presumably due to the storm, with the deepest erosion at KAT14 in rapidly accumulating sediments closest to Southwest Pass [*Corbett et al.*, 2006]. Lesser incisions are associated with lower modern sediment accumulation [*Corbett et al.*, 2006] (e.g., more consolidated surficial sediments). Seaward of 25 m to about 40 m water depth, the basal erosional surface was covered by the fining-upward event layer. The removal of surficial sediments down to a relict fluvio-deltiac material up to several thousand years old at inner sites suggests that tropical cyclones are a primary mechanism for keeping most of the inner shelf (<20 m) swept from modern sediments [*List et al.*, 1997; *Miner et al.*, 2009] despite the large flux of Mississippi-derived particulates moving alongshore in the westward-flowing coastal current. Further, this deflation by successive storms over decades, is likely a major factor generating retreat of inactive Mississippi deltaic lobe headlands. While winter cold-fronts likely contribute to this erosion on the shoreface (<10 m), significant wave heights (<1–2 m) during these events are generally too small to generate resuspension at greater depths [*Jaramillo et al.*, 2009]. Assuming a conservative 2 cm average shelf surface erosional deflation caused by Katrina for the area from the shoreline to the seaward edge of the erosional hiatal surface (~40 m water depth), and from Southwest Pass to the edge of our study area (~90.0W) in Figure 1 (2600 km^2), sediment yield at 1825 kg/m^3 would be ~95 million tons. This is equivalent to recent estimates of the total annual discharge of particulates transported down the main Mississippi pathway [*Horowitz*, 2010]. We conclude that hurricanes can be a significant budget component remobilizing POC from the inner shelf, ranging in age from years to thousands of years (see ^{14}C age discussion below), into the offshore deltaic depocenter. This also means that hurricanes 1) can create significant removal of older deposits in an area/water depth traditionally thought to be undergoing burial and preservation in the geologic record at Holocene timescales and 2) how if extrapolated over millennia, the collective removal of strata by hurricanes might eliminate much of the muddy prodelta deposit (see *Coleman et al.* [1998] for a facies outline).

[7] At the three sites shown as "2+ Events" in Figure 1 (e.g., KAT9, 10, 11), the surface of the Katrina deposit was incised by a later, erosional surface-event layer packet we attribute to the impact of Hurricane Rita which made landfall ~250 km west of the study area at the Texas-LA border the week prior to our cruise and caused large waves as far eastward as our study sites. Potentially, this event also contributed to the seabed deflation thicknesses measured inshore. At two of three "2+ Event" sites (KAT 9,10), the Katrina deposit was underlain by third packet that is probably associated with Hurricane Ivan in 2004 [*Dail et al.*, 2007; *Sampere et al.*, 2008]. It is uncertain why this multiple deposit is observed in this zone at water depths (20–25 m) that in adjacent regions (Figure 1) show no event layer preservation, but may be related to water and sediment sourced from adjacent Barataria Bay (see next section). However, these data demonstrate that stacked hurricane event layers are present in the last several decades of accumulation at these sites (based on core depths and known accumulation rates [*Corbett et al.*, 2006]), albeit in restricted areas, in deltaic shelf depocenters and if they extend to deeper sediment intervals, may be mined in future studies to determine cyclonic storm frequencies related to changing climate.

4. Sediment and Organic Matter Sources

[8] Seaward of about 40 m water depth, no incision surface was observed, suggesting that combined wave-current shear stresses were below critical erosion stress at these water depths during the storm. In several of these core sites, an event layer was still observable in X-radiographs as a change in fabric (grain size), supported by the presence of ^{7}Be activity. A more widespread mapping of these deeper sites [*Goñi et al.*, 2007] recognized a Katrina event layer as far west as the Atchafalaya shelf, where it overlapped with a

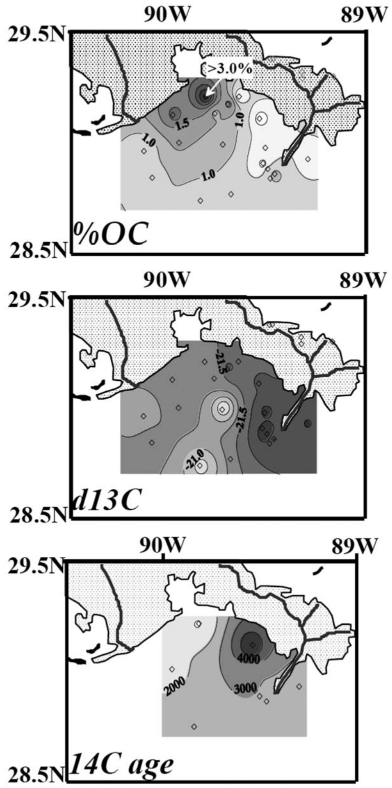

Figure 2. Bulk organic characteristics of surface sediments (0–1 cm interval) in the box cores collected in October 2005. (top) Organic carbon content (%), scale from 0.25% (white) to 3% (80% black); (middle) δ^{13}C (‰), scale from −20.5 (white) to −22.5 (80% black); (bottom) radiocarbon age (years), scale from 0 (white) to 6000y (80% black).

more substantial Rita event layer, and as deep as the floor of Mississippi Canyon. The deposition of a Katrina event layer seaward of the deflation zone suggests an offshore vector for sediment and organic matter driven by the ebbing storm surge. Values of OC in surficial (event layer) sediments are highest (>1.5%) on the inner shelf adjacent to Barataria Bay (Figure 2, top), supportive of a marsh-enhanced source (from erosion of marsh peats [*Wilson and Allison*, 2008]) carried offshore by the surge ebb. Conversely, the surficial sediments from the exposed relict inner shelf zone east of the Bay mouths (Figure 2, top) are low in OC (<1.0%). The δ^{13}C values (Figure 2, middle) from surficial sediments in both subareas show evidence of a mixed source (−20.5 to −23‰) assuming endmember mixing model averages (marine algae −21‰, C3 vascular plants −27‰, C4 vascular plants −13‰) [*O'Leary*, 1988; *Raymond and Bauer*, 2001]. These values are also similar to what has been observed for suspended sediments of the Mississippi-Atchafalaya River [*Goñi et al.*, 1997; *Onstad et al.*, 2000; *Gordon and Goñi*, 2004]. Further evidence of a marsh and bay source (from aged C3 marsh organic matter) comes from the fact that the youngest radiocarbon ages (ca. 1,000 y) for surficial sediments are found adjacent to the Bay, while relict sediments (exposed at the shelf surface at KAT7 east of the Bay) have a much older (>5,000 y) age (Table S1 and Figure 2, bottom). Downcore trends in POC character (site KAT9 in Figure 1) are related to the three stacked event layers observed in X-radiographs (Figure 3). The upper two layers are interpreted as a Katrina layer reworked by a subsequent event in Hurricane Rita (upper 9 cm). The activity of ^{7}Be extends to the base of the Katrina layer, but only into the upper 2–3 cm (likely due to bioturbation) of the oldest event layer (19–26 cm), which is interpreted as having been formed by Hurricane Ivan in 2004, based on previous rapid response observations of an Ivan event layer on the shelf [*Dail et al.*, 2007; *Sampere et al.*, 2008]. The percentage of OC increases upcore in the Katrina-Rita event layer, likely as a function of waning-phase fining upward sediment supply (e.g., increasing organic-rich clay fraction). Also, δ^{13}C values are relatively invariant, implying a relatively consistent source throughout all three event layers (−21.7 to −22.4‰), although there is an enrichment in the upper (0–5 cm), finer grain size Rita deposit, which is supportive of ebb surge wetland and Bay supply of marsh (C3-derived) OC at least in this event. The ^{14}C ages are relatively young (<1,600 yBP) throughout the core, also in agreement with a wetland source via the adjacent Bay. Overall, the bulk elemental and isotopic results are consistent with a localized deposition of relatively young and organic-rich material adjacent to Barataria Bay, low-OC relict sediments at the scour site, and redeposited shelf sediments that exhibit chemical composition similar to that delivered from the Mississippi River. Detailed examination of PAH isomer ratios in the core KAT4 [*Mitra et al.*, 2009] (Figure 1) Katrina layer were distinct from underlying sediment and from marshes on the eastern side of the delta (the location of these marsh sites is plotted in Figure 1). A possible explanation is that storm-caused petroleum leaks from

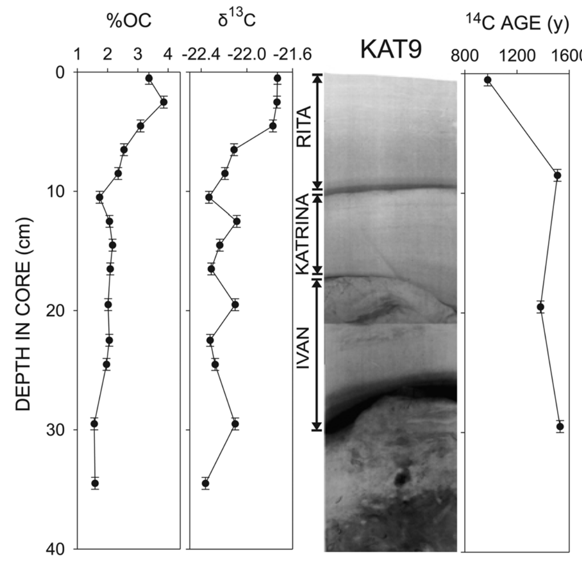

Figure 3. Downcore bulk organic characteristics for box core KAT9 (see Figure 1 for location) for organic carbon content (%), δ^{13}C (‰) and radiocarbon age (years) plotted alongside a core X-radiograph of stratigraphy. Errors for these analyses are discussed in the auxiliary material. The X-radiograph is displayed as a negative (dark = coarser): interpreted event layer (basal hiatal surface and upcore fining sediment package) depths for Hurricanes Rita (2005), Katrina (2005), and Ivan (2004) are displayed alongside the image. Horizontal lines at 21 and 30 cm depth in the X-radiograph are artifacts of the image stitching from multiple films.

tankers or refineries in coastal Louisiana reached this sample area, affecting PAH composition in a manner distinct from marshes on the eastern side of the delta, which were "upcurrent" of the deltaic plain (given that surge currents and transported wetland POC proceeded from east to west [*Knabb et al.*, 2006; *Barras*, 2006; *Turner et al.*, 2006]).

[9] The results support the idea that, while ultimately from the same sources (e.g., river, wetland, bay, shelf), the processes that excavate and deliver POC to the event layer sediments is distinct from the usual character of POC reaching these sites [*Sampere et al.*, 2008]. Likely, event layer muds in this region are a combination of sediment and OC from wetland erosion [*Barras*, 2006], Barataria Bay resuspension, and from remobilized sediments from modern and relict river-derived inner shelf deposits. Certainly the estimated mass of the Katrina+Rita event layer deposit on the shelf (1160 million tons [*Goñi et al.*, 2007]) is an order of magnitude larger than we estimate the shelf deflation sediment yield for Katrina above. The Mississippi River is likely an additional source, given that the most depleted values are observed proximal to the Southwest Pass river mouth (Figure 2b), although discharge is relatively low at this time of year. Previous studies have suggested that this largest shelf depocenter west of the river mouth tends to be dominated by the POC fingerprint of sediments supplied directly from the Mississippi River [*Gordon and Goñi*, 2004; *Allison et al.*, 2007; *Sampere et al.* 2008]. The lack of downcore POC evidence for a hurricane signature in these previous studies may suggest that these fractions are either 1) subject to rapid remineralization at or near the sediment-water interface if labile (wetland source) or 2) are also river-derived (shelf incision source) and difficult to distinguish, except perhaps through examination of compound specific ^{14}C ages or specific biomarkers) from POC freshly delivered from the river using bulk elemental and isotope analytical techniques. Implications for the re-introduction of labile material potentially include involvement in the redox oscillations associated with the periodic hypoxia that is prominent in this region [*Bianchi et al.*, 2010], and co-metabolism effects that would facilitate more complete remineralization of recalcitrant POC fractions downcore prior to burial [*Aller and Blair*, 2004, 2006]. Both fractions may potentially impact the POC burial efficiency, and hence the carbon budget, in river deltaic systems impacted by cyclonic storms.

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M. A. Allison, Institute for Geophysics, University of Texas at Austin, 10100 Burnet Rd., Austin, TX 78758-4445, USA. (mallison@mail.utexas.edu)

T. M. Dellapenna, Department of Marine Sciences, Texas A&M University at Galveston, PO Box 1675, Galveston, TX 77553, USA. (dellapet@tamug.edu)

E. S. Gordon, Department of Geo/Physical Sciences, Fitchburg State College, 160 Pearl St., Fitchburg, MA 01420-2697, USA. (egordon3@fsc.edu)

S. Mitra, Department of Geological Sciences, East Carolina University, 101 Graham Bldg., Greenville, NC 27858, USA. (mitras@ecu.edu)

S. T. Petsch, Department of Geosciences, University of Massachusetts at Amherst, 611 North Pleasant St., Amherst, MA 01003, USA. (spetsch@geo.umass.edu)