

DOES THE PEB INDEX RESPOND ONLY TO HYPOXIA IN THE MISSISSIPPI DELTA, GULF OF MEXICO?

HAL R. TICHENOR¹, STEPHEN J. CULVER^{1,3}, D. REIDE CORBETT¹, JOHN P. WALSH¹ AND MARTIN A. BUZAS²

ABSTRACT

The frequency of anthropogenic seasonal hypoxia on the continental shelf west of the Mississippi Delta (the Louisiana Bight) has increased since the middle of the 20th century. This study applies the PEB index, a proxy for hypoxia, to four ~2 m kasten cores taken southwest of Southwest Pass of the Mississippi Delta. The PEB index is defined as the cumulative percent of *Protonionion atlanticum* (= *Nonionella atlantica* of this study), *Nonionella opima*, *Epistominella vitrea* and *Buliminella morgani*. The PEB index varies little in the shallowest core, KC4 (59 m water depth). Assemblages were strongly dominated by PEB taxa (average 95%), due mainly to the dominance of *E. vitrea* (average 76%). In core KC3 (75 m), an average PEB value of 84% is also due mainly to *E. vitrea* (61%). The PEB index of KC3 was consistently higher above 90 cm, a level dated at 1955–1960 (²¹⁰Pb age estimate), and could reflect an increased influence of hypoxia or an increased rate of sediment accumulation associated with delta progradation. A similar trend characterizes core KC2 (87 m). The PEB index is 18% from 240 cm to 140 cm, increasing up core as the abundance of *E. vitrea* increases, likely due to delta progradation. Other PEB taxa, *B. morgani* and *N. opima*, increase in the top 30 cm of the core, probably due to increased hypoxia between 1952 and 1968 (²¹⁰Pb age estimate). Core KC1 (473 m) differed from shallower cores in its higher species diversity. *Bolivina lowmani*, *Cassidulina neocarinata*, and *Bolivina ordinaria* each comprise ~15% of assemblages and PEB taxa are rare (average 5%) but increase to 19% in a 30 cm interval attributed to off-shelf transport. We conclude that the PEB index is a useful indicator of anthropogenic hypoxia but dominance of *E. vitrea* may also be attributable to sedimentological factors related to delta progradation.

INTRODUCTION

Hypoxia, dissolved oxygen levels of <2 mg/L (2.8 ml/L; Pavela et al., 1983; Leming & Stuntz, 1984; Renaud, 1986), is the condition in which oxygen concentrations in water are low enough to have a negative effect on aquatic life. Extensive studies of coastal hypoxia commenced in the 1980s as hypoxic events, resulting from anthropogenic effects such as fertilizer-related nutrient loading from rivers, were becoming more prevalent (Nixon, 1997; Gooday et al., 2009). Direct records of hypoxia reach back only to 1985 (CENR, 2000). Foraminiferal assemblages, however, provide a longer history of hypoxia at many locations (e.g., North Adriatic Sea, Barmawidjaja et al., 1995; Mississippi

Delta, U.S.A., Blackwelder et al., 1996; Chesapeake Bay, U.S.A., Karlson et al., 2000; Drammensfjord, Norway, Alve, 2000; Long Island Sound, U.S.A., Thomas et al., 2000; St. Lawrence Estuary, Canada, Thibodeau et al., 2006; Gulf of Tehuantepec, Mexico, Vásquez-Bedoya et al., 2008; Osaka Bay, Japan, Tsujimoto et al., 2008).

The Mississippi Bight (Fig. 1) has the second largest coastal anthropogenic hypoxic zone in the world (Rabalais et al., 2007a) with a recorded maximum area of 22,000 km² and an average of 13,500 km² between 1985 and 2009 (Rabalais et al., 2010). The hypoxic zone (4–60 m water depth) has increased in size from 8,200 km² in 1985–1992 to 10,500 km² in 2003–2007 (CENR, 2000; Rabalais et al., 2007a), though proxies indicate that hypoxia was increasing before field measurements began. Rabalais et al. (2007b) and Osterman et al. (2009) reviewed the timing of this increase. Using foraminiferal data, Osterman et al. (2009) suggested that the general area near the Mississippi River Delta experienced hypoxia as far back as the early 1900s and noted that more hypoxia occurred further west by the mid-1900s. However, the area adjacent to and directly southwest of Southwest Pass of the Mississippi Delta was previously unstudied.

Hypoxia in the northern Gulf of Mexico is a consequence of stratification of the water column resulting from freshwater input from rivers, combined with the decomposition on the seafloor of organic matter from phytoplankton blooms (CENR, 2000). The outflow of the Mississippi and Atchafalaya Rivers create a layer of warmer, fresher water on top of the salty water of the Gulf of Mexico, preventing oxygen transport through dispersion or vertical mixing (Wiseman et al., 1997). Stratification is most prominent from mid-May through mid-September and is broken up by winter storms; thus, hypoxia occurs seasonally (Rabalais & Turner, 2001). The size and persistence of seasonal hypoxic events increase when Mississippi River and Atchafalaya River discharge increases (Wiseman et al., 1997; CENR, 2000). The rivers bring nutrients (e.g., nitrogen, phosphorus, and silica) that facilitate the growth of phytoplankton that eventually sink to the seabed and provide carbon for decomposition (Turner, 2002). This decomposition reduces dissolved oxygen in the bottom water (Rabalais et al., 1991; Eadie et al., 1994; Turner & Rabalais, 1994).

The purpose of this study is to provide a detailed benthic foraminiferal record of the high sediment input area immediately southwest of Southwest Pass, thus elucidating of the history of hypoxia southeast of the region sampled by the Nutrient Enhanced Coastal Ocean Productivity program (Rabalais et al., 1991). Foraminiferal assemblages from four ~2m cores, taken along a transect from near Southwest Pass across the shelf to the Mississippi Canyon (Fig. 1), are used to investigate hypoxia in this region.

¹Department of Geological Sciences, East Carolina University, Greenville, NC, 27858, USA

²Department of Paleobiology, National Museum of Natural History, Smithsonian Institution, Washington, D.C., 20560, USA

³Correspondence author. E-mail: culvers@ecu.edu

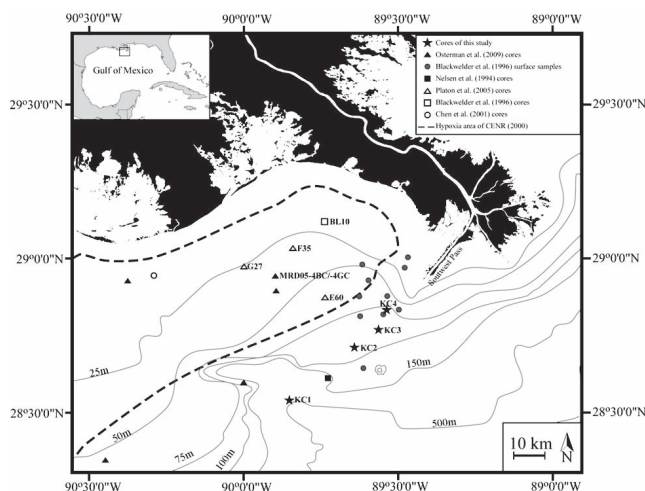


FIGURE 1. Map of the study area showing locations of cores KC1–KC4; (KC2–KC4 are from the Mississippi Delta and KC1 is from the Mississippi Canyon) and core and sample sites from Blackwelder et al. (1996), Nelson et al. (1994), Chen et al. (2001), Platon et al. (2005) and Osterman et al. (2009). The outline (dashed line) of the area in the eastern Louisiana Bight affected by hypoxia is taken from CENR (2000).

FORAMINIFERA AS PROXIES FOR HYPOXIA

Foraminiferal assemblages in the seasonally hypoxic area of the Louisiana Bight have lower species richness, lower overall abundances, lower relative abundances of agglutinated and porcelaneous foraminifera, and increases in species tolerant of oxygen stresses (e.g., Nelsen et al., 1994; Blackwelder et al., 1996; Sen Gupta et al., 1996; Platon & Sen Gupta, 2001; Osterman, 2003; Brunner et al., 2006; Rabalais et al., 2007b). To understand hypoxia, three proxies have been established: the *Ammonia-Elphidium* (A-E) index (Sen Gupta et al., 1996), the agglutinated–porcelaneous (A-P) index (Platon et al., 2005) and the *Protonionion atlanticum*, *Epistominella vitrea*, and *Buliminella morgani* (PEB) index (Osterman, 2003).

The A-E index is calculated by $[N_A/(N_A + N_E)] \times 100$, where N_A is the amount of *Ammonia parkinsoniana* and the N_E is the amount of *Elphidium excavatum*. Increasing abundances of the stress-tolerant *A. parkinsoniana*, and decreasing abundances of *E. excavatum*, result in an increase in the A-E index, indicating increasing hypoxia. The A/E index is used in waters shallower than 30 m, as the percentages of *A. parkinsoniana* and *E. excavatum* drop below useful levels in deeper waters (Platon & Sen Gupta, 2001). The reliability of this proxy for hypoxia has been questioned as it may be influenced by other factors such as changes in the nature of the food supply, turbidity and substrate instability (Brunner et al., 2006).

Platon et al. (2005) suggested the A-P index, which utilizes the percentages of all agglutinated and porcelaneous taxa. These taxa become less abundant relative to calcareous hyaline taxa as hypoxia increases, sometimes disappearing from the assemblage completely (Rabalais et al. 1996, 2000; Sen Gupta et al., 1996; Platon et al., 2005). The index reflects the decreasing diversity common in hypoxia-influenced samples and was found to correlate well with glauconite

abundance and the concentration of biogenic silica (Platon et al., 2005).

Nelsen et al. (1994) and Blackwelder et al. (1996) recognized an association of particular foraminiferal species (*Buliminella morgani*, *Nonionella opima*, *Epistominella vitrea* and other taxa) with hypoxia. Osterman (2003) later proposed the PEB index, calculated as the combined relative abundance of *Pseudonion atlanticum*, *E. vitrea*, and *B. morgani*. However, high abundance of *E. vitrea* has been related to environmental factors other than hypoxia. Blackwelder et al. (1996) pointed out that high densities of *E. vitrea* are correlated with the Mississippi River discharge plume as well as low oxygen environments. In a study within the 1995 hypoxic zone, Platon & Sen Gupta (2001) suggested that tests of the dominant *E. vitrea* were transported into the study area by the Mississippi River plume. Perhaps related to high sediment input, *E. vitrea* has been described as migrating upwards in the sediment seasonally, suggesting high infaunal mobility (Barmawidjaja et al., 1992). *Epistominella vitrea* has been also been associated with high input of phytodetritus (Gooday & Hughes, 2002; Langezaal et al., 2006; Duchemin et al., 2007; Mojtahid et al., 2008).

Variations of the PEB index from within the hypoxic zone indicate that five intervals of hypoxia, attributed to natural increases in river flow resulting in more intense stratification and increased nutrients, occurred in the Louisiana Bight between 1100 BP and the 1900s (Osterman et al., 2008). Sen Gupta et al. (1996) documented one of the earliest signs of anthropogenic hypoxia in core G27 (Fig. 1). The A/E index has increased since the 1800s, with a higher rate of increase in the 1900s. This environmental shift at the turn of the 20th century is seen in several proxies, such as the 1870s disappearance of the hypoxia-sensitive *Quinqueloculina* in core G27 (Fig. 1; Rabalais et al. 1996, 2000; Sen Gupta et al., 1996; Platon et al., 2005). The foraminiferal assemblage of core BL10 (Fig. 1) shows a trend of decreasing species richness and a stronger influence of the low-oxygen adapted *B. morgani* starting as early as ~1910 (Nelsen et al., 1994; Blackwelder et al., 1996). Foraminiferal proxies for hypoxia, however, show a sharp increase around the 1950s–1960s (Blackwelder et al., 1996; Rabalais et al., 1996, 2000, 2007b; Sen Gupta et al., 1996; Platon & Sen Gupta, 2001; Platon et al., 2005; Osterman et al., 2005, 2008, 2009), correlating with an increase in the extent and duration of seasonal hypoxia. This change is attributed largely to the increased flux of nutrients, primarily nitrogen in the form of nitrate, from the Mississippi and Atchafalaya Rivers (Rabalais et al., 1996, 1999; CENR, 2000; Rabalais & Turner, 2001, 2006; Goolsby et al., 2001; Stow et al., 2005).

METHODS

FORAMINIFERAL SAMPLES

Four ~2 m kasten-type gravity cores were collected during September 2007 along a transect southwest of Southwest Pass to the Mississippi Canyon (Fig. 1; Appendix 1) at water depths of 59 m, 75 m, 87 m, and 473 m. Immediately after collection, the cores were X-radiographed, wrapped in polyvinylidene chloride film, and stored in a cooler. On return to the laboratory, 1 cm samples (10 cc) were taken at 10 cm

intervals and dried overnight at $\sim 35^{\circ}\text{C}$. Dried samples were weighed and then disaggregated in water with ~ 0.13 g of sodium hydroxide to aid disaggregation. Samples were washed over 710 μm and 63 μm sieves to remove coarse material and mud, and the >63 μm material was picked for foraminifera. Approximately 200 specimens of benthic foraminifera were picked for each sample from randomly selected squares on a picking tray. Foraminifera were identified to the species level using classic references (e.g., Phleger & Parker, 1951; Parker, 1954). Identifications were confirmed via comparison with type and figured specimens (Appendix 2) at the Smithsonian Institution, Washington, D.C.

^{210}Pb ANALYSIS

The ^{210}Pb activity was quantified via alpha spectroscopy following a modified method of Nittrouer et al. (1979). Samples were ground to a fine powder, then 1.0–1.5 g were spiked with a ^{209}Po tracer as a yield determinant and digested for >12 hours in 8N HNO_3 prior to a high temperature, high pressure, acid-leach in a CEM microwave reaction system (MARS 5). The $^{210}, ^{209}\text{Po}$ were electrodeposited onto a nickel disc from the acidic solution following a modified version of Flynn (1968). Supported levels of ^{210}Pb from decaying ^{226}Ra were obtained from samples where ^{210}Pb had reached a stable level deep in the core. Supported ^{210}Pb was subtracted from total ^{210}Pb activities to obtain excess ^{210}Pb activities. Linear sediment accumulation rates were determined via:

$$A_x = A_0 e^{-\lambda x/S}$$

where A_x represents the excess ^{210}Pb activity at depth x (cm); A_0 represents the excess ^{210}Pb activity at the bottom boundary of the mixed layer; λ is the day constant of ^{210}Pb (0.031 yr^{-1}); and S is a linear sediment accumulation rate (cm yr^{-1} ; Appleby & Oldfield, 1992).

NUMERICAL ANALYSIS

The PEB taxa were present in all cores. *Nonionella atlantica* (= *Protonion atlanticum* of Osterman, 2003) was rare and was grouped with *N. opima*, a morphologically similar species, to obtain PEB values (analogous to the methodology of Osterman et al., 2006). Cluster analysis (Mello & Buzas, 1968) using Ward's linkage and Euclidean distance was performed on data from each core. Foraminiferal abundance data were transformed using an arcsine square-root transformation on the relative abundances of all species (Bartlett, 1947).

RESULTS

SEDIMENTOLOGY AND SEDIMENTATION RATES

Each core was composed of dark green-gray mud. The >63 μm fraction of each sample was primarily foraminiferal tests. The X-radiographs of the four cores demonstrated the presence of a few slightly sandier intervals. In particular, the top ~ 5 cm of Core KC2 was sandier and represents a bioturbated hurricane unit (Rabien et al., 2015). A single sample was taken from the top of this section (0–1 cm). The down-core profile of ^{210}Pb activity from KC2 is shown in Figure 2.

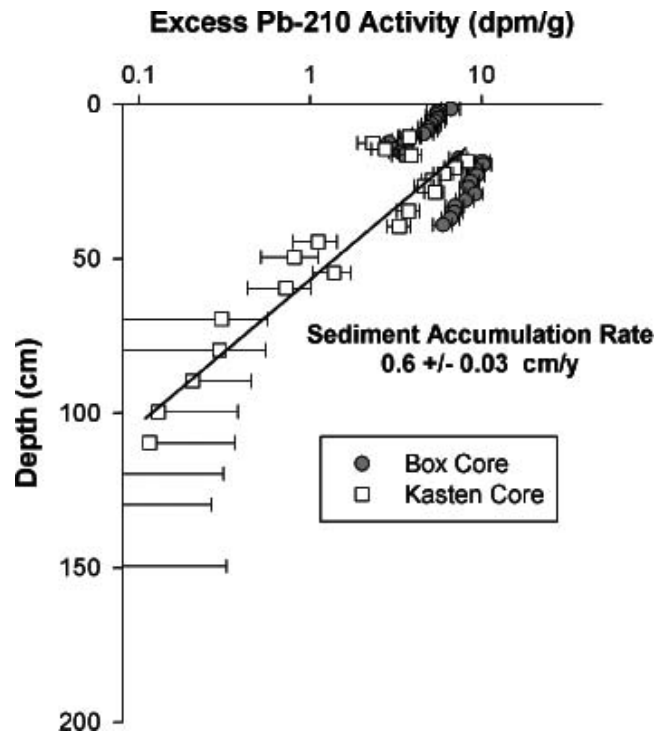


FIGURE 2. The line represents the accumulation rate determined for KC2 using excess ^{210}Pb activity below the shift at ~ 18 cm (~ 10 cm sample depth in the kasten core) due to a hurricane deposit above this depth (Rabien et al., 2015). Box-core data are from Rabien et al. (2015).

This core was chosen for ^{210}Pb analysis because it contained two distinct core depth-related cluster groups. Comparison of the ^{210}Pb activity in kasten core KC2 to a box core (Fig. 2) collected at the same time at the same site (Rabien et al., 2015) gives an estimated loss of 8 cm of sediment from the top of the kasten core during coring operations. A sediment accumulation rate of 0.6 ± 0.03 cm/y was determined from the KC2 excess ^{210}Pb data below the influence of the hurricane unit. The ^{210}Pb activity of KC3 was not analyzed due to instrument failure, but a sediment accumulation rate of 2.0 ± 0.5 cm/y (Corbett et al., 2006) from a core collected at the same site during a previous cruise was applied to KC3 (assuming a loss of 32 cm of sediment estimated when the core was collected). Activity values of ^{210}Pb for KC1 and KC4 were not determined as their foraminiferal assemblages showed no significant trends with depth.

FORAMINIFERAL ASSEMBLAGES

From KC4 (59 m water depth), 32 species were identified from 25 samples (Appendix 3). The average percentage of planktonics was 1.2% [Standard Error (SE) = 0.2] and average species richness (S) was 8 (SE = 0.5; Fig. 3). *Epistominella vitrea* dominated all samples (Appendix 3) and comprised an average of 76% (SE = 2.0) of assemblages. *Buliminella morgani* and *Nonionella opima* were common, averaging 11% (SE = 1.0) and 8% (SE = 1.4) respectively (Appendix 3).

From core KC3 (75 m), 35 species were identified from 20 samples (Appendix 3). The average percentage of planktonics was 4.0% (SE = 0.5) and average species richness (S) was 12 (SE = 0.2), both higher than in KC4 (Fig. 3). *Epistominella vitrea* averaged 61% (SE = 2.4) of assemblages

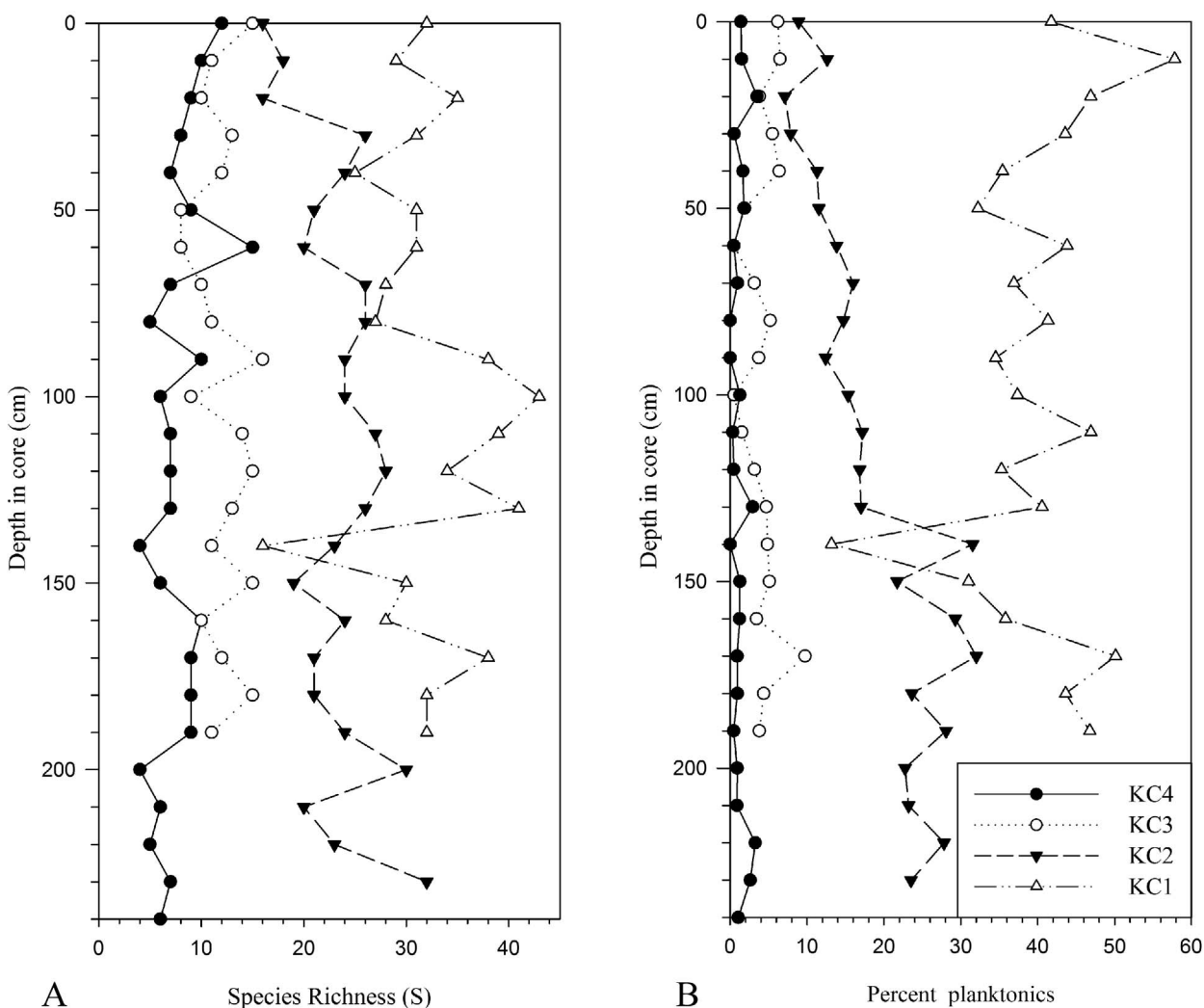


FIGURE 3. Plots of (A) Species richness and (B) percent planktonics for cores KC1–KC4.

and *B. morgani* averaged 18% (SE = 1.5); all other taxa averaged <5% of the total core assemblage (Appendix 3).

From core KC2 (87 m), 60 species were identified from 20 samples (Appendix 3). The average percentage planktonics of 19% (SE = 2.4) and the average species richness (S) of 23 (SE = 0.8) were higher than in KC3 (Fig. 3). The percent planktonics decreased steadily up core above 130 cm (Fig. 3). *Epistominella vitrea* was again the most abundant taxon but averaged much less (31%; SE = 3.3) than in KC4 and KC3 (Appendix 3). Species evenness was higher than in KC3 and KC4, with *Bolivina lowmani*, *Uvigerina peregrina*, *Bulimina marginata*, and *Bolivina barbata* each comprising >5% of the assemblages in KC2.

The 20 samples from core KC1, within the Mississippi Canyon (473 m), contained 78 species, 27 of which did not occur in the shelf cores (Appendix 3). The average percentage of planktonics was 40% (SE = 3.4) and the average species richness (S) was 32 (SE = 1.3), both higher than in the shelf cores (Fig. 3). *Bolivina lowmani*, common in the shelf cores, and deeper water taxa *Paracassidulina neocarinata* and *Bolivina ordinaria*, were the most abundant taxa, with average relative abundances of 15% (SE = 3.0), 15% (SE = 3.8) and 13% (SE = 2.4), respectively (Appendix 3).

PEB INDEX

Epistominella vitrea was the main contributor to the PEB index in every sample of each core (Fig. 4). The PEB index decreased with increasing water depth. In the shallowest core (KC4), the index averaged 95% (SE = 0.6) but ranged as high as 99.6% (Fig. 4). A slight decrease in relative abundance of *E. vitrea* was recorded from 170 to 190 cm in KC4 (Fig. 4). The PEB index was 83% (SE = 1.9) in Core KC3, with higher average values (90%, SE = 1.0) above 80 cm and lower average values (76%, SE = 1.7) below (Fig. 4). In KC3, the relative abundance of *E. vitrea* increased in the top 40 cm while the relative abundance of *Buliminella morgani* decreased in the same interval. The average PEB index for KC2 was less than half that of KC3 at 38% (SE = 4.5). The PEB index below 140 cm in KC2 averaged 19% (SE = 1.8), increasing to the top at a peak value of 84% (Fig. 4). The up-core increase in the PEB index in KC2 was due to an increase in percent *E. vitrea* until the upper 30 cm of the core, where *B. morgani* and *N. opima* increased in abundance, with a combined average of 23% (SE = 1.4) above 30 cm compared to 3.7% (SE = 0.5) below that depth (Fig. 5). The PEB taxa were relatively rare in

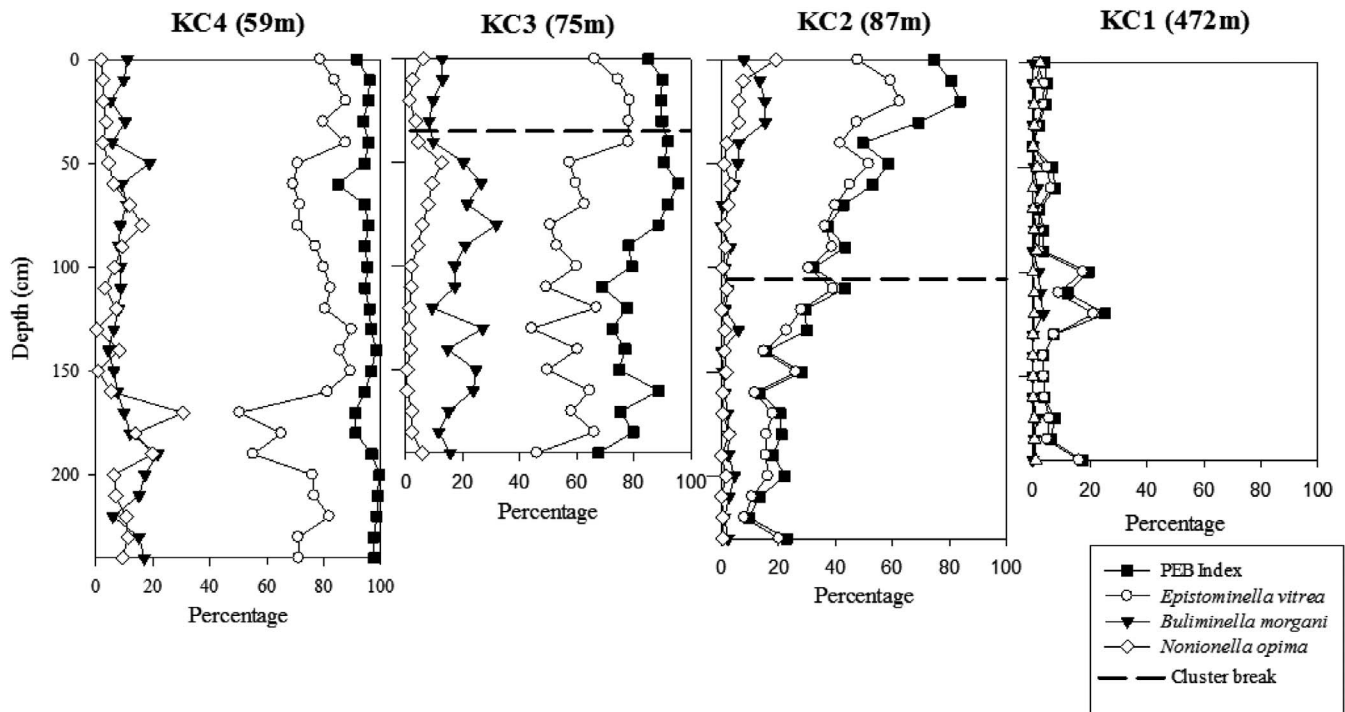


FIGURE 4. The PEB index of each sample from the four cores is shown together with the percent abundance of the taxa comprising the index.

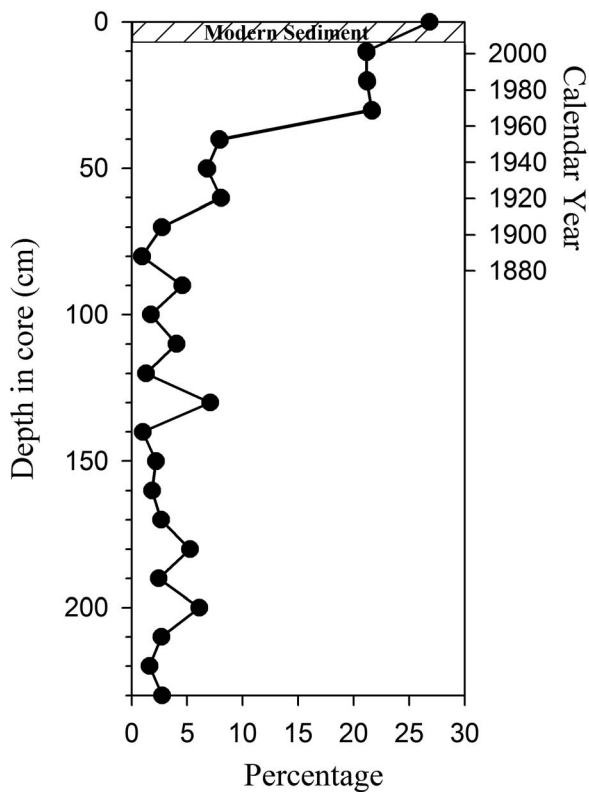


FIGURE 5. The combined percentage of *Buliminella morgani*, *Nonionella opima* and *N. atlantica* in core KC2, with dates derived from ^{210}Pb age estimates. The dates start below the first point due the loss of sediment during retrieval of the core and the emplacement of hurricane-related sediment during 2004 and 2005 ("modern sediment").

KC1 (Fig. 4), averaging only 7% (SE = 1.4) of the assemblage. However, between 100 cm and 120 cm the PEB index averaged 19%.

CLUSTER ANALYSES

Cluster analyses did not group samples by depth in KC4 (59 m) or KC1 (473 m; Fig. 6) because, as indicated in Figure 4, the assemblages change very little throughout the length of these cores. Cluster analysis of KC3 (75 m; Figs. 4, 6) distinguished the top 40 cm (group 1) from the rest of the core (group 2). Although group 2 as a whole contains more taxa than group 1 (Table 1), both groups have a similar mean species richness (S) of 12. The assemblage of group 1 is dominated by the PEB taxon, *E. vitrea*, with an average of 75% (SE = 2.4) of the assemblage; *E. vitrea* represents 56% (SE = 2.4) of the assemblage in group 2 (Table 1). *Buliminella morgani* is twice as abundant in group 2 as in group 1 (Table 1).

Cluster analyses of the foraminiferal assemblages of core KC2 (87 m) distinguished the top 110 cm of the core (group 1) from the rest (group 2; Figs. 4, 6). Both groups have similar mean species richness values, 22 and 24 for groups 1 and 2, respectively. Group 1 is dominated by *E. vitrea* (mean percent abundance of 45%; SE = 3.9) whereas Group 2 has a more even distribution and *E. vitrea* is less dominant (mean percent abundance of 17%, SE = 1.6; Table 2). *Bolivina lowmani* is also common with a mean percent abundance of 16% (SE = 1.2). Other PEB taxa, *Nonionella opima* and *B. morgani*, do not vary much between the two groups and have a combined average of ~10% in each group (Table 2).

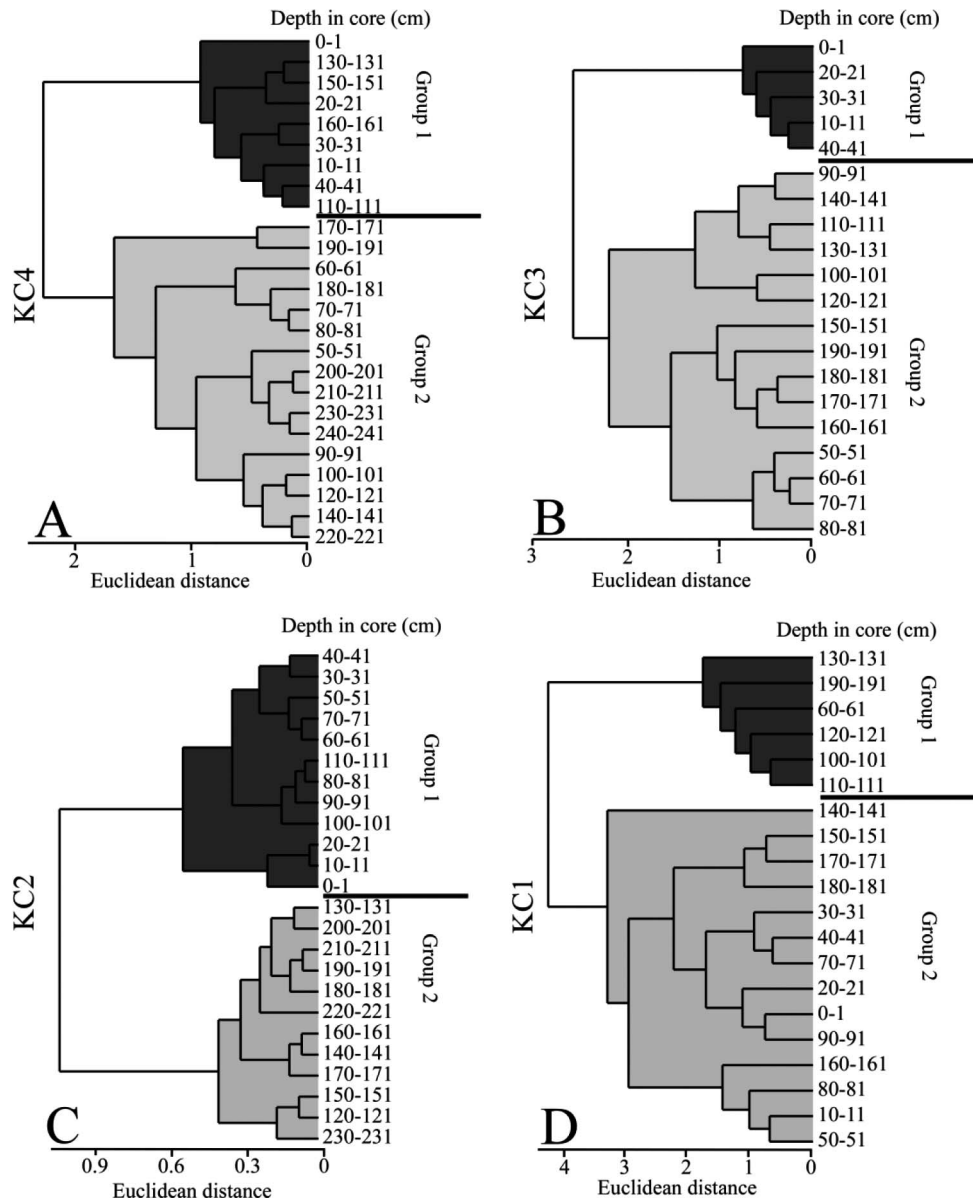


FIGURE 6. Dendrograms showing the results of cluster analysis of each core

Cluster analyses of all samples from the four cores defined four groups, each composed primarily of samples from a single core (Fig. 7). Group 1 represents the diverse assemblages of core KC1 and is distinguished from the rest of the cores. Most samples of KC2 are in group 4 but three samples, where *N. opima* and *B. morgani* are more abundant, are clustered in group 3 with the bottom portion of KC3. In core KC3, the lower samples clustered in group 3 and the upper samples, characterized by higher PEB index values, clustered with the high PEB index samples of core KC4 in group 2.

DISCUSSION

SPECIES RICHNESS AND PERCENT PLANKTONICS

The average species richness and relative abundance of planktonic foraminifera in the cores increase with water depth (Fig. 3). Cores KC4 and KC3, from shallower water

and areas of higher sedimentation, have consistently low percentages of planktonics (>6%). In the deeper shelf core KC2, planktonics average 26% (SE = 1.2) below 130 cm and then decrease in abundance steadily towards the core top, where they are as low as 7% (Fig. 3B). This trend is not seen in species richness of KC2 (Fig. 3A) although *Epistominella vitrea* increases in abundance at the same depth (Fig. 4), possibly resulting in a lower relative abundance for planktonics rather than an actual decrease in the density. The relative abundance of planktonics and species richness are much higher in core KC1, with the exception of the sample at 140 cm that contained anomalously abundant *Bulimina striata mexicana* (Appendix 3). This subspecies can occur as shallow as 100 m in the Gulf of Mexico (Phleger & Parker, 1951), but it is typical of waters deeper than 600 m (Pflum & Frerichs, 1976).

TABLE 1. Mean percent abundance of taxa in groups defined by cluster analysis of the foraminiferal assemblage data in core KC3.

Group 1 (0-40 cm) 5 samples, 21 taxa	Mean %	Group 2 (50-190 cm) 15 samples, 32 taxa	Mean %
<i>Epistominella vitrea</i>	75.11	<i>Epistominella vitrea</i>	56.35
<i>Buliminella morgani</i>	10.68	<i>Buliminella morgani</i>	19.85
<i>Bolivina lowmani</i>	4.12	<i>Bolivina lowmani</i>	5.01
<i>Nonionella opima</i>	3.62	<i>Uvigerina peregrina</i>	4.77
<i>Bolivina cf. B. daggarius</i>	1.35	<i>Nonionella opima</i>	3.98
<i>Uvigerina peregrina</i>	1.35	<i>Bolivina cf. B. daggarius</i>	3.51
<i>Bulimina marginata</i>	0.67	<i>Textularia earlandi</i>	1.32
Indeterminate rotaliids	0.67	<i>Bulimina marginata</i>	1.11
<i>Bolivina striatula spinata</i>	0.59	<i>Bolivina striatula spinata</i>	0.76
<i>Bolivina translucens</i>	0.25	<i>Islandiella cf. I. subglobosa</i>	0.59
<i>Lenticulina cf. L. peregrina</i>	0.25	<i>Bolivina barbata</i>	0.41
<i>Quinqueloculina sp. C</i>	0.25	<i>Ammotium salsum</i>	0.32
<i>Buliminella elegantissima</i>	0.17	<i>Quinqueloculina spp.</i>	0.32
<i>Elphidium excavatum</i>	0.17	<i>Globobulimina miss.</i>	
<i>Fursenkoina pontoni</i>	0.17	Indeterminate rotaliids	0.23
<i>Quinqueloculina sp. B</i>	0.17	Indeterminate textulariids	0.23
<i>Bolivina barbata</i>	0.08	<i>Pyrgo nasutus</i>	0.20
<i>Islandiella cf. I. subglobosa</i>	0.08	<i>Bolivina daggarius</i>	0.15
<i>Lagena spp.</i>	0.08	<i>Bolivina subaenariensis mex.</i>	0.09
<i>Quinqueloculina spp.</i>	0.08	<i>Quinqueloculina sp. D</i>	0.09
Indeterminate textulariids	0.08	<i>Elphidium gunteri</i>	0.06
		<i>Elphidium excavatum</i>	0.06
		<i>Fursenkoina pontoni</i>	0.06
		<i>Quinqueloculina sp. A</i>	0.06
		<i>Ammonia parkinsoniana</i>	0.03
		<i>Ammonia tepida</i>	0.03
		<i>Bolivina goesii</i>	0.03
		<i>Bulimina gibba</i>	0.03
		<i>Elphidium mexicanum</i>	0.03
		<i>Lagena spp.</i>	0.03
		<i>Lenticulina cf. L. peregrina</i>	0.03
		<i>Quinqueloculina sp. C</i>	0.03

HIGH PEB INDEX VALUES AND SIEVE SIZE

The PEB taxa, *Nonionella opima* (plus *N. atlantica* = *Protonion atlanticum* of Osterman, 2003), *E. vitrea*, and *Buliminella morgani*, comprise 85–100% of foraminiferal assemblages in core KC4 (Fig. 4). This results in an average PEB index of 95% (SE = 0.1). Every sample but one in KC4 has a higher PEB index than all samples investigated by Osterman et al. (2009), who reported a maximum PEB index value of 89%. Osterman et al. (2009) used a core (MRD05-4GC; Fig. 1) from the within the hypoxia zone (Rabalais et al., 1999) to define a long-term background level for the PEB index of 12%. In a separate core (BL-10; Fig. 1), they described values over 50% as very high (Osterman et al., 2009). Thus, the average PEB index of 95% in KC4 is extremely high, despite being outside the hypoxic zone (Fig. 1).

Since *E. vitrea* is generally smaller than the other PEB taxa, the size fraction of foraminifera assessed affects the PEB index in areas where *E. vitrea* is very abundant. Osterman et al. (2009) used the >125 μm fractions, whereas we used the >63 μm fraction. Picking the >125 μm fractions can obscure some details of the environmental record inferred from foraminiferal data from the 63–125 μm

TABLE 2. Mean percent abundance of taxa in groups defined by cluster analysis of the foraminiferal assemblage data in core KC2.

Group 1 (0-110 cm) 12 samples, 50 taxa	Mean %	Group 2 (120-230 cm) 12 samples, 54 taxa	Mean %
<i>Epistominella vitrea</i>	45.31	<i>Epistominella vitrea</i>	16.52
<i>Uvigerina peregrina</i>	12.20	<i>Bolivina lowmani</i>	16.28
<i>Bolivina lowmani</i>	7.47	<i>Uvigerina peregrina</i>	10.54
<i>Bulimina marginata</i>	6.37	<i>Bolivina barbata</i>	10.26
<i>Buliminella morgani</i>	6.37	<i>Bulimina marginata</i>	9.11
<i>Nonionella opima</i>	4.22	<i>Buliminella morgani</i>	9.11
<i>Bolivina barbata</i>	3.97	<i>Eponides turgidus</i>	4.44
<i>Bolivina striatula spinata</i>	1.29	<i>Eponides repandus</i>	3.17
<i>Bolivina subaenariensis mex.</i>	1.25	<i>Bolivina subaenariensis mex.</i>	2.58
Indeterminate rotaliids	1.22	Indeterminate rotaliids	2.34
<i>Eponides turgidus</i>	0.97	<i>Islandiella cf. I. subglobosa</i>	1.94
<i>Islandiella cf. I. subglobosa</i>	0.82	<i>Cibicides spp.</i>	1.82
Indeterminate miliolids	0.72	<i>Valvulineria mexicana</i>	1.23
<i>Lenticulina cf. L. peregrina</i>	0.68	<i>Bolivina striatula spinata</i>	0.87
<i>Bolivina cf. B. daggarius</i>	0.64	<i>Gavelinopsis praegeri</i>	0.87
<i>Gavelinopsis praegeri</i>	0.64	<i>Elphidium excavatum</i>	0.75
<i>Elphidium excavatum</i>	0.50	<i>Lagena spp.</i>	0.75
Indeterminate textulariids	0.43	<i>Nonionella opima</i>	0.75
<i>Hanzawaia strattoni</i>	0.39	<i>Cibicides robertsonianus</i>	0.71
<i>Cibicides spp.</i>	0.36	<i>Hanzawaia strattoni</i>	0.48
<i>Lagena spp.</i>	0.36	<i>Fissurina spp.</i>	0.44
<i>Ammonia tepida</i>	0.32	<i>Uvigerina auberiana</i>	0.40
<i>Eponides repandus</i>	0.32	<i>Ammonia tepida</i>	0.36
<i>Valvulineria mexicana</i>	0.29	Indeterminate miliolids	0.36
<i>Cibicides robertsonianus</i>	0.25	<i>Lenticulina cf. L. peregrina</i>	0.32
<i>Quinqueloculina spp.</i>	0.25	<i>Buliminella elegantissima</i>	0.28
<i>Quinqueloculina sp. C</i>	0.21	<i>Eponides regularis</i>	0.28
<i>Ammotium salsum</i>	0.18	<i>Lenticulina calcar</i>	0.28
<i>Bulimina aculeata</i>	0.18	<i>Sagrina pulchella</i>	0.28
<i>Buliminella elegantissima</i>	0.18	<i>primitiva</i>	
<i>Globobulimina mississippiensis</i>	0.18	<i>Quinqueloculina spp.</i>	0.24
<i>Pyrgo nasutus</i>	0.18	<i>Globobulimina mississippiensis</i>	0.20
<i>Bolivina translucens</i>	0.14	<i>Quinqueloculina sp. B</i>	0.20
<i>Bolivina daggarius</i>		<i>Islandiella norcrossi australis</i>	0.16
<i>Paracassidulina neocarinata</i>	0.11	<i>Pyrgo nasutus</i>	0.16
<i>Fursenkoina complanata</i>	0.11	Indeterminate textulariids	0.16
<i>Fursenkoina pontoni</i>	0.11	<i>Bolivina cf. B. daggarius</i>	0.12
<i>Bolivina fragilis</i>	0.11	<i>Islandiella sp. A</i>	0.12
<i>Fursenkoina mexicana</i>	0.07	<i>Quinqueloculina sp. C</i>	0.12
<i>Gaudryina spp.</i>	0.07	<i>Quinqueloculina sp. D</i>	0.12
<i>Islandiella norcrossi australis</i>	0.07	<i>Sigmoilina spp.</i>	0.12
<i>Lenticulina calcar</i>	0.07	<i>Ammonia parkinsoniana</i>	0.08
<i>Nonionella atlantica</i>	0.07	<i>Bolivina daggarius</i>	0.08
<i>Textularia earlandi</i>	0.07	<i>Fursenkoina mexicana</i>	0.08
<i>Ammonia parkinsoniana</i>	0.04	<i>Fursenkoina pontoni</i>	0.08
<i>Bolivina goesii</i>	0.04	<i>Quinqueloculina sp. A</i>	0.08
<i>Fissurina spp.</i>	0.04	<i>Textularia candeiana</i>	0.08
<i>Marginulina marginulinoides</i>	0.04	<i>Ammotium salsum</i>	0.04
<i>Quinqueloculina sp. D</i>	0.04	<i>Bolivina fragilis</i>	0.04
<i>Sigmoilina spp.</i>	0.04	<i>Paracassidulina neocarinata</i>	0.04
		<i>Elphidium mexicanum</i>	0.04
		<i>Fursenkoina complanata</i>	0.04
		<i>Gaudryina spp.</i>	0.04
		<i>Hoeghündina elegans</i>	0.04
		<i>Marginulina marginulinoides</i>	0.04

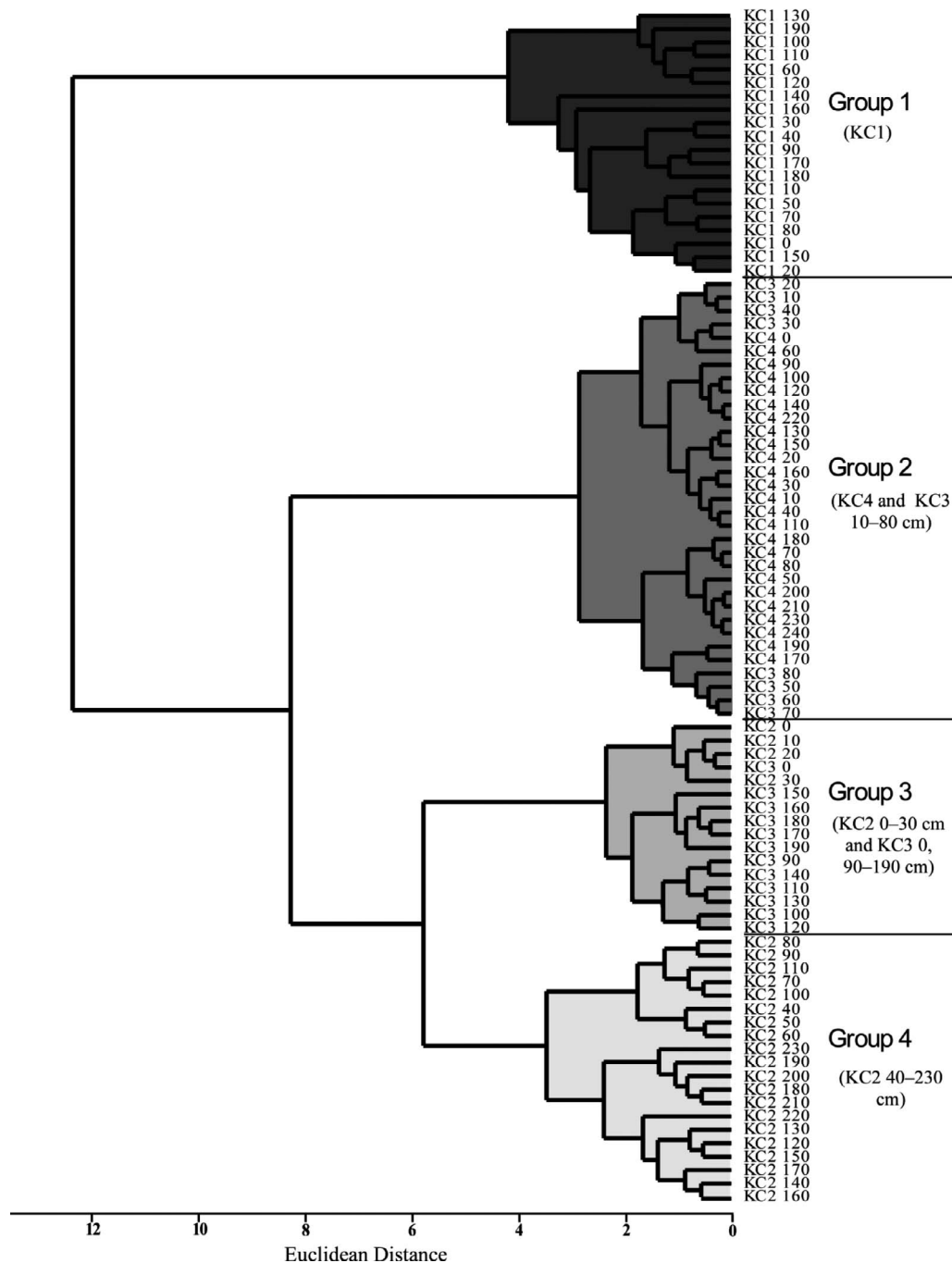


FIGURE 7. Dendrogram showing the results of cluster analysis of all cores combined.

fraction. For example, small outer-shelf to abyssal foraminiferal species are likely opportunistic and increase in abundance during eutrophication (Goody, 1988, 1993; Kitazato et al., 2000; Duchemin et al., 2007). Osterman et al. (2009), in contrast, chose to exclude specimens $<125 \mu\text{m}$ to reduce the swamping effect of one small species and because this approach is less time-consuming. Use of the $>125 \mu\text{m}$ fraction is also recommended by the Foraminiferal Bio-Monitoring (FOBIMO) initiative (Schonfeld et al., 2012) when studying live foraminifera for environmental monitoring. Moodley et al. (1997) suggested the use of $38 \mu\text{m}$ or $45 \mu\text{m}$ sieves in certain environments, such as those experiencing

anoxia, because even using the $>63 \mu\text{m}$ size fraction led to underestimates of the abundance of certain foraminiferal taxa

Use of a standard sieve size of $63 \mu\text{m}$ has been suggested for environmental studies (Schröder et al., 1987; Sen Gupta et al., 1987). This sieve size has been utilized in much recent research including that of foraminiferal proxies for hypoxia in the Gulf of Mexico (e.g., Blackwelder et al., 1996; Sen Gupta et al., 1996; Platon et al., 2005; Brunner et al., 2006). Picking at the $>63 \mu\text{m}$ level allows for a compromise between the time it takes to pick samples and completeness of the assemblages, and enables comparison with much of

the previous work on foraminifera in the Gulf of Mexico. The PEB index values of Platon et al. (2005) range up to >90%, similar to values in the current study. Blackwelder et al. (1996) also recorded high PEB index values, around 70%. This indicates that sieve size contributes to the higher PEB index in KC4 compared to the Osterman et al. (2009) work, but is likely not the only factor.

DELTA PROGRADATION AND ABUNDANCE OF *EPISTOMINELLA VITREA*

In several studies in the hypoxic zone that utilized the >63 μm size fraction, *E. vitrea* contributions to the PEB index were low. For example, in core 10 of Blackwelder et al. (1996; BL10 in Platon et al., 2005; Osterman et al., 2008, 2009; Fig. 1), *E. vitrea* comprised an average of 31% of the PEB index and in core F35 of Platon et al. (2005; Fig. 1), *E. vitrea* comprised an average of 33% of the PEB index. These data suggest that environmental conditions near Southwest Pass related to Mississippi River influence may be an important factor contributing to the high abundance of *E. vitrea* in KC4, in addition to sieve size. This is supported by data from core E60 (Fig. 1) of Platon et al. (2005), taken only ~20 km west of KC4, which has a higher average relative abundance of *E. vitrea* at 44% of the PEB index. In surface samples near the mouth of Southwest Pass (Blackwelder et al., 1996), only 2 km from KC4 (Fig. 1), the average PEB index was 78%, with *E. vitrea* comprising an average of 60%. In the surface samples of Blackwelder et al. (1996) from the center of the Louisiana Bight, farther away from Southwest Pass, *E. vitrea* comprised an average of 26% of the PEB index in samples with PEB index values >12%, the minimum value for areas of lower-oxygen values determined by Osterman et al. (2008, 2009).

Ecological controls on the abundance of *E. vitrea* are complex. Blackwelder et al. (1996) attributed the high abundance of *E. vitrea* near Southwest Pass to the higher sedimentation rates of this area. Indeed, the sites of KC4 and KC3 exhibit the highest sedimentation rates reported from the Louisiana Bight (Corbett et al., 2006). In some laboratory studies, *E. vitrea* has been observed migrating within sediment in response to hypoxia (Alve & Bernhard, 1995), but in other studies *E. vitrea* showed no response to hypoxia (Ernst et al., 2005). This species has also been recorded as increasing in abundance in response to the presence of organic matter (Gooday & Hughes, 2002; Langezaal et al., 2006). Thus, hypoxia and abundant organic matter, which are related conditions, can affect the abundance of *E. vitrea*, but sedimentary processes involved in delta progradation (high sedimentation and mudflows; Corbett et al., 2006; Walsh et al., 2006) may be the primary controlling factors in foraminiferal assemblage composition in areas adjacent to Mississippi River outflow.

TEMPORAL TRENDS IN *EPISTOMINELLA VITREA*

The interpretation that *E. vitrea* has changed in abundance due to environmental changes other than hypoxia explains why this species shows temporal trends that differ from those for other PEB taxa (Fig. 4). In the lower part of core KC2, *E. vitrea* shows little variation in abundance (~23%) until above the 140 cm core-depth, where it

increases upwards to 83% at 20 cm. The other PEB taxa, *N. opima* and *B. morgani*, have a combined average of 3.7% (SE = 0.5) below 40 cm and 23% (SE = 1.4) above (Fig. 4), suggesting that *N. opima* and *B. morgani* are responding to different environmental variables or the same variables at different thresholds. The upward trend in *E. vitrea* is paralleled by the trend of decreasing relative abundance of planktonics above 140 cm and up to 20 cm (Fig. 3B). The decrease in planktonics suggests the trend up core from 140 cm represents an increasing density of *E. vitrea* in the sediment. This trend in KC2 represents an up-core shift to an assemblage more typical of shallower water cores, indicating delta progradation as a causative factor.

RECORD OF HYPOXIA

If *E. vitrea* is not considered in the PEB index for KC2, a different trend is seen that may indicate the increased influence of hypoxia on the foraminiferal assemblage near the top of this core. *Nonionella opima* and *B. morgani* increase in combined abundances between 40 cm and 30 cm (from 8% to 22%; Fig. 4) and this likely represents anthropogenically increased hypoxia. Using the ^{210}Pb age estimates, this change occurred between 1952 and 1968, accounting for the 8 cm loss of material from the core top and the 18-cm post-2004 hurricane deposit. Core KC3 shows an increase in PEB taxa above 80 cm (Fig. 4), but not as strong as the three-fold increase of *N. opima* and *B. morgani* seen in the top 30 cm of KC2. In KC3, the PEB index is higher in the upper part of the core with an average index of 90% (SE = 0.10) above 80 cm and 76% (SE = 1.74) below (Fig. 4). Above 50 cm, the relative abundance of *E. vitrea* increases while those of *N. opima* and *B. morgani* decrease. This shift in the relative abundance of taxa that comprise the PEB index does not change the value of the index as a whole, but again suggests a shift in environmental conditions, possibly a stronger influence from the Mississippi River. The increase in the PEB index in KC3 takes place between 90 cm and 80 cm. The ^{210}Pb data (Corbett et al., 2006) indicate that this shift occurred between 1955 and 1960. This timing agrees quite well with the change in relative abundance of *N. opima* and *B. morgani* in KC2. These dates also agree well with the evidence of increasing PEB index in the Louisiana Bight in the mid-20th century (Osterman et al., 2008, 2009). Other studies of foraminiferal assemblages in this region document an increasing influence from hypoxia from the late 1940s to the early 1960s (Sen Gupta et al., 1996; Platon & Sen Gupta, 2001; Platon et al., 2005; Osterman et al., 2009) as do other indicators of hypoxia such as total marine organic matter, percent biologically-bound silica, phytoplankton assemblages, and pigment concentrations from anoxygenic bacteria (Turner et al., 2004; Eadie et al., 1994; Rabalais et al., 1996, 2000, 2004, 2007b; Chen et al., 2001).

In addition to PEB taxa, several other species in KC2 and KC3 are found in low-oxygen settings and contribute to the indication of a hypoxic environment. *Bolivina lowmani* is the second most abundant species in KC2 and the third most abundant in KC3, and did not change in relative abundance in a core that showed an increasing influence of hypoxia (Blackwelder et al., 1996). Three other common species in

cores KC3 and KC2, *Uvigerina peregrina*, *Bulimina marginata*, and *Bolivina subaenariensis*, can respire nitrate, thus making them more resilient during periods of hypoxia (Piña-Ochoa et al., 2010).

The CENR (2000) revealed hypoxia as deep as 60 m to the west of the Mississippi delta. Foraminiferal data from KC3 (75m) and KC2 (87 m) suggest hypoxia occurs unusually deep in the study area or that PEB taxa in these cores have been transported down slope. Storm-driven sediment gravity flows of the prograding deltaic system have been reported in this region (Walsh et al., 2006; Goni et al., 2007). However, the tiny, delicate PEB taxa (well-preserved in this study) could be transported downslope primarily in suspension, thus avoiding breakage. Down-slope transport is supported by the co-occurrence of the deeper water taxa, *Uvigerina peregrina* and *Bulimina marginata* (comprising an average of 11% and 8% percent of the assemblages), with PEB taxa in KC2. Mississippi Canyon core KC1 also shows evidence of down-slope transport of PEB taxa. The PEB index averages 5% in this core, but from 100 to 130 cm it increases to ~15% (Fig. 4), although the lithology does not change.

CONCLUSIONS

Very high PEB index values off Southwest Pass, when compared with samples from other studies in the Louisiana Bight, could be interpreted as indicating that the study area is experiencing extensive and strong hypoxia. However, the increase in abundance of *Epistominella vitrea* towards Southwest Pass suggests that this species is responding to sedimentological processes (e.g., high sedimentation rates and sediment gravity flows) related to Mississippi River discharge. The increased abundance of *E. vitrea* towards the top of cores KC2 and KC3 is interpreted to be a reflection of delta progradation in this region. *Buliminella morgani*, *Nonionella opima* and *N. atlantica*, however, show different trends than *E. vitrea* in cores KC2 and KC3, and began increasing in relative abundance in the 1950s. This timing agrees with other records of hypoxia in the Louisiana Bight and suggests that these taxa do indicate hypoxia. Thus, the use of the PEB index as a simple indicator of hypoxia in the area near Southwest Pass is somewhat problematic. High relative abundances of *B. morgani*, *N. opima*, and *N. atlantica* are indicators of hypoxia, while high abundances of *E. vitrea* are likely indicative of Mississippi River-related sedimentary processes.

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APPENDIX 1. Core metadata.

Core name	Date taken	Latitude	Longitude	Water depth (m)	Core length (cm)
PEL0907KC4	9/19/2007	28°51.867 N	89°31.638 W	59	240
PEL0907KC3	9/19/2007	28°48.382 N	89°33.002 W	75	190
PEL0907KC2	9/19/2007	28°45.545 N	89°37.918 W	87	230
PEL0907KC1	9/19/2007	28°34.728 N	89°49.176 W	473	190

APPENDIX 2

Taxonomic Reference List

- Ammonia parkinsoniana* (d'Orbigny) = *Rosalina parkinsoniana* d'Orbigny, 1839, p. 99, pl. 4, figs. 25–27.
- Ammonia tepida* (Cushman) = *Rotalia beccarii* (Linné) var. *tepida* Cushman, 1926, p. 79, pl. 1, figs. 8a–c.
- Ammotium salsum* Cushman and Brönnimann, 1948, p. 39, pl. 7, fig. 9.
- Anomalinoidea mexicana* Parker, 1954, p. 539, pl. 11, figs. 21–23.
- Bolivina alata* (Seguenza) = *Vulvulina alata* Seguenza, 1862, p. 115, pl. 2, figs. 5.
- Bolivina albatrossi* Cushman, 1922, pt. 3, p. 31, pl. 6, fig. 4.
- Bolivina barbata* Phleger and Parker, 1951, p. 13, pl. 6, figs. 12a, b, 13.
- Bolivina daggarius* Parker = *Bolivina lanceolata* Parker, 1954, p. 514, pl. 7, figs. 17–20.
- Bolivina fragilis* Phleger and Parker, 1951, p. 13, pl. 6, figs. 14, 23, 24a, b.
- Bolivina goesii* Cushman, 1922, pt. 3, p. 34, pl. 6, fig. 5.
- Bolivina lowmani* Phleger and Parker, 1951, p. 13, pl. 6, figs. 20a, b, 21.
- Bolivina minima* Phleger and Parker, 1951, p. 14, pl. 6, figs. 22a, b, 25; pl. 7, figs. 1, 2.
- Bolivina ordinaria* Phleger and Parker = *Bolivina simplex* Phleger and Parker 1951, p. 14, pl. 7, figs. 4–6.
- Bolivina striatula spinata* Cushman = *Bolivina striatula* var. *spinata* Cushman, 1936, p. 59, pl. 8, figs. 9a, b.
- Bolivina subaenariensis mexicana* Cushman = *Bolivina subaenariensis* var. *mexicana* Cushman, 1922, pt. 3, p. 47, pl. 8, fig. 1.
- Bolivina subspinescens* Cushman, 1922, pt. 3, p. 48, pl. 7, fig. 5.
- Bolivina translucens* Phleger and Parker, 1951, p. 15, pl. 7, figs. 13, 14a, b.
- Bulimina aculeata* d'Orbigny, 1826, p. 269, n. 7.
- Bulimina alazanensis* Cushman, 1927, p. 161, pl. 25, fig. 4.
- Bulimina marginata* d'Orbigny, 1826, p. 269, pl. 12, figs. 10–12.
- Bulimina striata mexicana* Cushman = *Bulimina striata* var. *mexicana* Cushman, 1922, pt. 3, p. 95, pl. 21, fig. 2.
- Buliminella elegantissima* (d'Orbigny) = *Bulimina elegantissima* d'Orbigny, 1839, p. 51, pl. 7, figs. 13, 14.
- Buliminella morgani* Andersen, 1961, p. 87, pl. 19, fig. 10.
- Cassidulina carinata* Silvestri = *Cassidulina laevigata* d'Orbigny var. *carinata* Silvestri, 1896, p. 104, pl. 2, fig. 10a–c.
- Cassidulina crassa* d'Orbigny, 1839, p. 56, pl. 7, figs. 18–20.
- Cassidulina tenuis* Phleger and Parker, 1951, p. 27, pl. 14, figs. 14–17.
- Chilostomella oolina* Schwager, 1878, p. 527, pl. 1, fig. 16.
- Cibicides robertsoniana* (Brady) = *Truncatulina robertsonianus*, Brady, 1881, v. 21, p. 65.
- Cibicides umbonatus* Phleger and Parker, 1951, p. 31, pl. 17, figs. 7–9.
- Elphidium excavatum* (Terquem) = *Polystomella excavata* Terquem, 1876, p. 469, pl. 2, figs. 2a–d.
- Elphidium gunteri* Cole, 1931, p. 34, pl. 4, figs. 9, 10.
- Epistominella vitrea* Parker, Phleger and Pierson, 1953, p. 9, pl. 4, figs. 34–36, 40, 41.
- Eponides antillarum* (d'Orbigny) = *Rotalina antillarum* d'Orbigny, 1839, p. 75, pl. 5, figs. 4–6.
- Eponides regularis* Phleger and Parker, 1951, p. 21, pl. 11, figs. 3a, b, 4a–c.
- Eponides repandus* (Fichtel and Moll) = *Nautilus repandus* Fichtel and Moll, 1803, p. 35, pl. 3, figs. a–d.
- Eponides turgidus* Phleger and Parker, 1951, p. 22, pl. 11, figs. 9a, b.
- Fursenkoina complanata* (Egger) = *Virgulina complanata* Egger, 1893, p. 292, pl. 8, figs. 91, 92.
- Fursenkoina mexicana* (Cushman) = *Virgulina mexicana* Cushman, 1922, pt. 3, p. 120, pl. 23, fig. 8.
- Fursenkoina pontoni* (Cushman) = *Virgulina pontoni* Cushman, 1932, p. 17, pl. 3, fig. 7.
- Fursenkoina tessellata* Phleger and Parker, 1951, p. 19, pl. 9, figs. 15, 16.
- Gavelinopsis translucens* (Phleger and Parker) = “*Rotalia*” *translucens* Phleger and Parker, 1951, p. 24, pl. 12, figs. 11a, b, 12a, b.
- Globobulimina mississippiensis* Parker, 1954, p. 511, pl. 7, figs. 3, 4, 10.
- Gyroidina altiformis* Stewart and Stewart, 1930, p. 67, pl. 9, fig. 2a–c.
- Gyroidina orbicularis* d'Orbigny, 1826, p. 278, n. 13.
- Hanzawaia strattoni* (Applin) = *Truncatulina americana* var. *strattoni* Applin et al., 1925, p. 99, pl. 3, fig. 8.
- Hoeglundina elegans* (d'Orbigny) = *Rotalia elegans* d'Orbigny, 1826, p. 276, n. 54.
- Hopkinsina atlantica* Cushman = *Hopkinsina pacifica* var. *atlantica* Cushman, 1944, p. 30, pl. 4, fig. 1a–c.
- Islandiella nocrossi australis* Phleger and Parker, 1951, p. 27, pl. 14, figs. 8a, b, 9, 10.
- Lenticulina calcar* (Linné) = *Nautilus calcar* Linné, 1758 p. 1162, n. 272.
- Lenticulina peregrina* Schwager, 1866, p. 245, pl. 7, fig. 89.
- Lenticulina thalmani* Hessland, 1943, pl. 1, 2.
- Marginulina marginulinoidea* (Goës) = *Cristellaria aculeata* var. *marginulinoidea* Goës, 1896, p. 56, pl. 5, figs. 15, 16.
- Nonionella atlantica* Cushman, 1947, p. 90, pl. 20, figs. 4, 5.
- Nonionella opima* Cushman, 1947, p. 90, pl. 20, figs. 1–3.
- Nonionoides turgida* (Williamson) = *Rotalina turgida* Williamson, 1858, p. 50, figs. 95–97.
- Oridorsalis umbonatus* (Reuss) = *Rotalina umbonatus* Reuss, 1851, p. 75, pl. 5, figs. 35a–c.
- Paracassidulina neocarinata* (Thalman) = *Cassidulina laevigata* d'Orbigny var. *carinata* Cushman, 1922, pt. 3, p. 124, pl. 25, figs. 6, 7.
- Pseudononion atlanticum* (Cushman) = *Nonionella atlantica* Cushman, 1947, p. 11, pl. 5, figs. 21–23.
- Pyrgo nasutus* Cushman, 1935, p. 7, pl. 3, figs. 1–4.
- Sagrina pulchella* (Cushman) = *Bolivina pulchella* var. *primitiva* Cushman, 1930, p. 47, pl. 8, figs. 12a, b.
- Sigmoilina distorta* Phleger and Parker, 1951, p. 8, pl. 4, figs. 3–5.
- Siphonina pulchra* Cushman, 1919, p. 42, pl. 14, figs. 7a–c.
- Texularia candeiana* d'Orbigny, 1839, p. 143, pl. 1, figs. 19, 20.
- Textularia earlandi* Parker, 1952, p. 458.
- Uvigerina laevis* Goës = *Uvigerina auberiana* (d'Orbigny) var. *laevis* Goës, 1896, p. 51.
- Uvigerina peregrina* Cushman, 1923, p. 166, pl. 42, figs. 7–10.

APPENDIX 3

Foraminiferal census data. This appendix can be found on the Cushman Foundation website in the JFR Article Data Repository (<http://www.cushmanfoundation.org/jfr/index.html>) as item number JFR_DR 2016001.