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HYPOXIA HOTSPOTS IN THE MISSISSIPPI BIGHT

Charlotte A. Brunner[1], Jennifer M. Beall[2], Samuel J. Bentley[3] and Yoko Furukawa[4]

ABSTRACT

Foraminiferal proxies of hypoxia indicate apparent low oxygen to hypoxic conditions in several hotspots in the Mississippi Bight. The foraminiferal hypoxia proxies, the *Ammonia* to *Elphidium* (A/E) index and the *Pseudononion-Epistominella-Buliminella* (PEB) index, were tabulated from three sets of core tops collected in 1951–1956. Additionally, the oxygenation history of a site near the Balize delta was evaluated over the past one hundred years based on A/E and PEB indices and size distributions of pyrite framboids in a gravity core dated by ^{210}Pb geochronology.

The results from the 1950's core-top collections show apparent, recurrent low-oxygen to hypoxic bottom water on the inner shelf at hotspot locales seaward of the Mississippi-Alabama barrier islands and the eastern distributaries of the Balize delta. Specifically, the A/E index exceeds 90% on the inner shelf seaward of Horn and Dauphin islands, both of the Mississippi-Alabama barrier islands, and a center between Pass à Loutre and Main Pass of the Balize delta. In partial support of these results are reports of present-day low oxygen to hypoxic concentrations in bottom waters associated with seasonally high surface chlorophyll a and seasonal strengthening of a brackish-water cap at these locales. In contrast, the PEB index in core tops suggests good oxygenation at mid-shelf depths >30 m. The PEB index, size distributions of framboidal pyrite, and other indicators in a gravity core 44 km northeast of Pass à Loutre indicate no clear change in conditions over the past century, constraining the seaward extent of the hotspot near the Balize delta.

INTRODUCTION

Hypoxia plagues bottom waters of the Louisiana continental shelf west of the Mississippi delta (Rabalais and others, 1994), and concern has arisen that recurrent, seasonal hypoxia might be developing on the Mississippi shelf as well. Like the Louisiana Bight, brackish water caps much of the Mississippi Bight during late spring and summer. The nutrient-rich river water at the surface both stimulates production and isolates water beneath it from oxygen replenishment. The resultant rain of organic matter to the seafloor fuels respiration that could lead to hypoxia (oxygen concentration $\leq$ 2 mg/l) if oxygen is not replenished.

Recently, there have been worrisome reports of low-oxygen events and even hypoxia in limited areas of the Mississippi Bight. Discrete events of low oxygen appear in the Southeast Area Monitoring and Assessment Program (SEAMAP) environmental surveys at various times during summer months from 1982 to 2003 (Gulf States Marine Fisheries Commission, 1982–2004). Even the central Bight occasionally experiences bouts of low oxygen (i.e., 2003, 2001, 1998), but events occur most frequently at specific locales: seaward of the Mississippi-Alabama barrier islands; immediately east of the Balize delta and its distributaries; and at depth along the outer shelf (Fig. 1). Low-oxygen and hypoxic events have been documented in the Mississippi Bight by other studies in addition to SEAMAP. Discrete measurements of hypoxia were reported on the inner shelf east of the Chandeleur Islands (Jochens and others, 2000), on the shelf seaward of passes between barrier islands of the Mississippi Sound (Christmas, 1973; Turner and Allen, 1982; Anonymous, 1984; Rabalais, 1992), north of the Chandeleur Islands (Turner and Allen, 1982), in Mobile Bay (Turner and others, 1987; Rabalais, 1992), on the shelf at 25 m water depth south of Pensacola (Jochens and others, 2000), and on the middle shelf 44 km northeast of Pass à Loutre (Maclean, 2002). In response to plummeting fish catches at its artificial reef, Fish Haven 2 (FH-2), the Mississippi Department of Marine Resources (DMR) began monthly measurements of temperature, salinity and oxygen profiles starting in October of 2003. They observed hypoxic bottom conditions throughout August of 2004 at two stations near the reef, which is located in 20 m of water south of Horn Island (Joe Jewell, written communication, 2004). Instances of hypoxia in discrete areas of the Bight are credible and spark questions about its history in the region.

Based on prior studies, several factors are known to affect hypoxia in the Bight, though their interactions and relative importance remain unclear. Subtropical Underwater covers the shelf, where freshwater input modifies its salinity, temperature, nutrient, particulate and oxygen concentrations. The Mississippi River is the principal source of freshwater to the study area, though additions of freshwater from other local sources, such as Lake Pontchartrain, Mobile Bay, the Pascagoula River and the Pearl River, are likely important at locales immediately seaward of the barrier islands. In spring and summer, the plume of the Mississippi River typically extends 40 km (Jochens and others, 2002) or more eastward of the delta, driven by seasonal, westerly winds (Morey and others, 2003). The plume brings with it nutrients and enhanced surface productivity (Lohrenz and others, 1999; see also SeaWiFS imagery; Naval Research Laboratory, 2004a), with associated salinity stratification, remineralization of nutrients, and oxygen utilization near the seafloor (Jochens and others, 2002; Wiseman and others, 1997). The summertime, brackish-water cap in the Mississippi Bight seems less steady in position than that in the Louisiana

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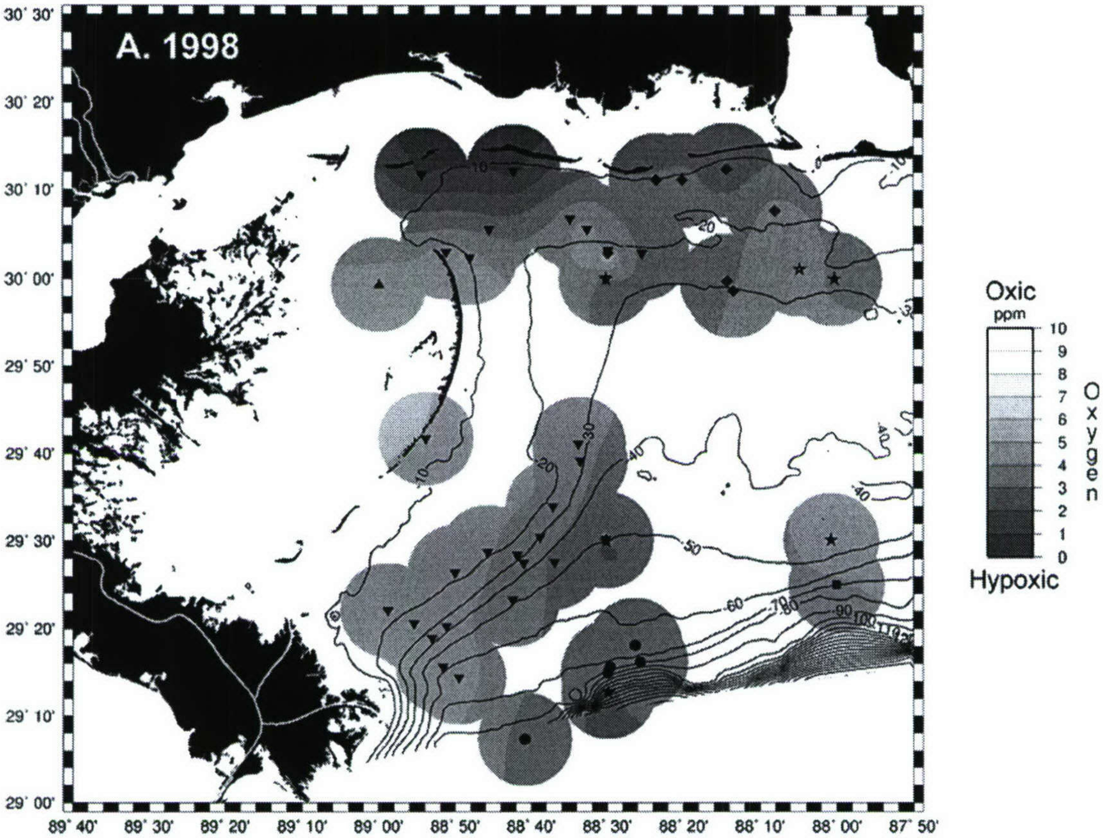

FIGURE 1. Bottom-water oxygen concentrations (ppm) sampled by SEAMAP (Gulf States Marine Fisheries Commission, 1982–2004) from two selected years: A. 1998, a year of normal river flow, when hypoxia appeared seaward of the Mississippi-Alabama barrier islands.

Bight. It surges inshore and offshore with the passage of eddies (Naval Research Laboratory, 2004b), providing opportunities for oxygen replenishment of bottom waters. Some of the cap can spin off with eddies, squirt past the shelf-edge in offshore jets, or flow as coastal currents from the region. However, the cap remains in place most of the time near the main passes from the Mississippi River and the Mississippi Sound. The potential for hypoxia caused by these factors is highest in the summer, when storms that could stir the water column are infrequent and, as long as eddies do not force cross-shelf exchange, flow from the Mississippi River and Sound is adequate to help maintain water column stability.

PROXIES OF HYPOXIA

Foraminifers

Foraminifers have been successfully used as proxies of hypoxia in many marine environments, including in the northern Gulf of Mexico. Foraminifer tolerance to anoxia for several species was convincingly demonstrated in laboratory tests (Moodley and Hess, 1992; Bernhard, 1993; Bernhard and Alve, 1996; Moodley and others, 1998) and, though the physiology responsible remains poorly understood, their tolerance has been well documented in field settings. Several research groups have independently shown that distributions of benthic foraminifers in core tops respond to the present-day seasonal recurrence of hypoxia on the Louisiana continental shelf (Blackwelder and others, 1996; Platon and Sen Gupta, 2001; Osterman and others, 2001; Osterman, 2003; Platon and others, 2005). Strong hypoxic effects were reported in core tops from the inner and middle shelf and more moderate but distinct effects from the outer shelf as deep as 60 m (Platon, 2001). These results were successfully applied to several high-resolution, shelf sediment records of the past 100–200 years (Blackwelder and others, 1996; Sen Gupta and others, 1996; Platon, 2001; Platon and Sen Gupta, 2001; Osterman and others, 2004; Osterman, 2005). In general, the foraminiferal records show that hypoxia events appeared above background levels in the 1940's and intensified in the 1960's in a pattern consistent with historical records of nitrate flux from the Mississippi drainage basin (Dinnel and Bratkovich, 1993). Sporadic occurrences of the hypoxic assemblage are also recorded in the 1800's in association with large floods (Osterman, 2005) that could have been exacerbated by land clearing and cultivation in the Mississippi drainage basin (Turner and Rabalais, 2003). Hypoxic assemblages have been identified and applied in other regions associated with major rivers (see review of van der Zwaan, 2000; van der Zwaan and Jorissen, 1991), polluted estuaries like the Chesapeake Bay (Karlsen and others, 2000), Long Island Sound (Thomas and others, 2000), and

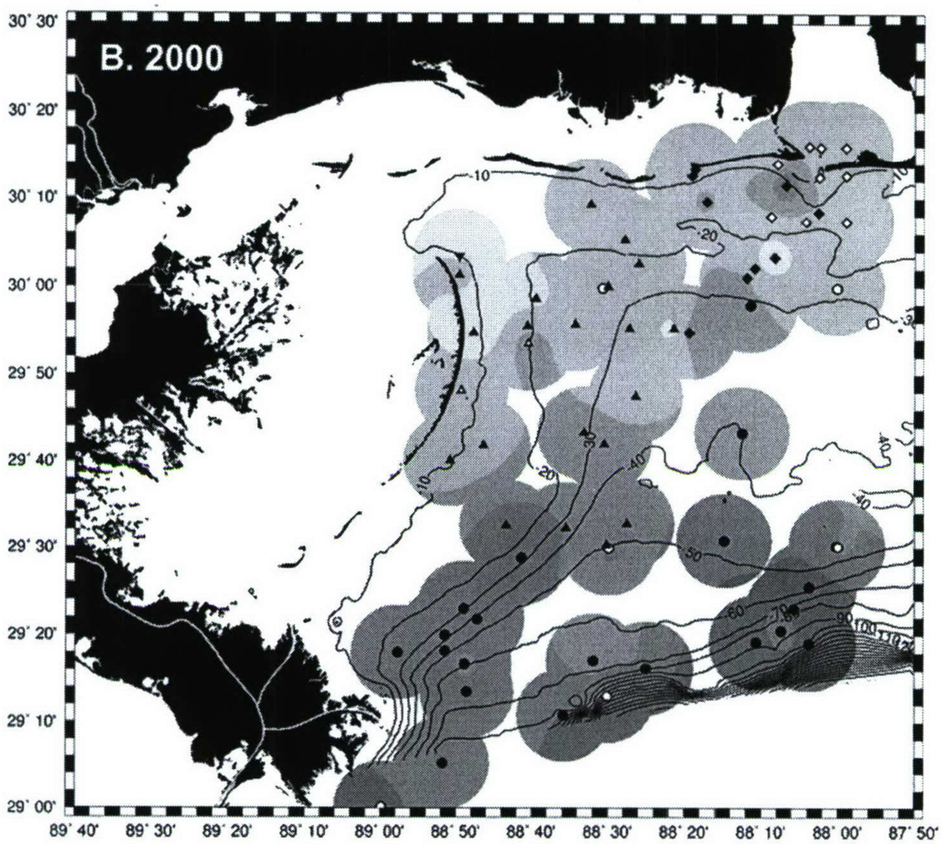

FIGURE 1. B. 2000, a drought year when oxygenation of bottom water was high in the bight, although low oxygen occurred at the shelf edge. The samples from each year were taken at various times from May through September, on different vessels (note different symbols) and with different instruments without effort to intercalibrate. The radius of the masking circles is 10 km. The scale of oxygen concentration in A applies also to B. Low oxygen recurs during the past 20 years seaward of the Mississippi-Alabama barrier islands, along the shelf break, and seaward of Main Pass and Pass à Loutre.

other low-oxygen settings (see Sen Gupta and Machain-Castillo, 1993, and references therein; Grantham and others, 2004).

Size of Pyrite Framboids

Framboidal pyrite forms when detrital iron minerals react with sulfide, which is produced by bacterial sulfate respiration (Berner, 1984). The framboids form in four steps (Wilkin and Barnes, 1997a): 1) nucleation and growth of iron monosulfide microcrystals; 2) transformation of microcrystals to greigite; 3) aggregation of greigite microcrystals into framboids, and 4) conversion of greigite to pyrite framboids. Steps 1 and 4 require reducing conditions, whereas step 2 requires weakly oxidizing conditions. Step 3 is mediated by the magnetic property of greigite. Laboratory results show that pyrite framboids form only in the presence of limited oxygen, like an oxic/anoxic boundary (Sweeney and Kaplan, 1973; Wilkin and Barnes, 1996). The oxygen appears to accelerate the conversion of iron monosulfide to pyrite (Wilkin and Barnes, 1996). Framboids form either in an anoxic water column prior to burial or in the anoxic pore water of sediments overlain by an oxic water column (Raiswell and Berner, 1985).

Pyrite framboid size and size distribution have been used as indicators of water-column oxygen conditions (Wilkin and Barnes, 1997a), although some controversy surrounds the application (Roychoudhury and others, 2003). Small framboids averaging ≤5 μm in diameter and with narrow size distributions form in anoxic water columns, whereas larger framboids of variable size form in anoxic pore waters of sediment overlain by oxic waters (Wilkin and others, 1996; Wilkin and Barnes, 1997). The theory behind this is based on the framboid growth rate and amount of time spent in the environment suitable for growth. In anoxic water columns, framboids form near the oxic-anoxic interface settle to the sea floor and cease to grow within centimeters of burial (Wilkin and others, 1996). In contrast, framboids that nucleate at an oxic/anoxic boundary in the sediment tend to reside in the growth environment for a longer period and grow to greater average size than those that form in the water column (Wilkin and others, 1996). The proxy has been tested in surface sediments and shallow cores from several anoxic, dysoxic and oxic environments, including the Black Sea, the Pettasquamscutt estuary (Narrow River) of Rhode Island, Framvaren Fjord of Norway (Wilkin and others, 1996) and Green Lake of Fayetteville, New York (Suits and Wilkin, 1998).

THE PROBLEM

The history of hypoxia on the neighboring Louisiana shelf is recorded by foraminifer proxies in sediment cores (Blackwelder and others, 1996; Sen Gupta and others, 1996; Osterman, 2004, 2005) and correlates well with historical records of increased flux of nutrients from the Mississippi river drainage basin. Nutrients rose above background levels by ~1930, and increased substantially after the mid-1950's, based on consumption of commercial fertilizers (Eadie and others, 1994). Loading doubled between 1960 and 1980 and has subsequently leveled off (Dinnel and Bratkovich, 1993). The anthropogenic loading is convincingly tied to hypoxia on the Louisiana shelf (Rabalais and others, 1996; Rabalais and Turner, 2001 and references therein; Rabalais, 2002; Dagg and others, 2004). It is reasonable to ask if conditions have also worsened in the Mississippi Bight since 1930 as nutrient loading has increased in the freshwater it receives from the Mississippi River and Mississippi Sound.

We use a two-pronged approach in a preliminary effort to address this question: (1) mapping of two foraminiferal proxies of hypoxia in core-top samples collected in 1951–1956 in the Bight, and (2) an historical study of faunal change in a ^{210}Pb-dated gravity core 44 km distant from the delta. The first study suggests the presence of persistent hypoxia in the 1950's seaward of the Mississippi-Alabama barrier islands and immediately east of the Balize delta. The second study tracks the oxygenation history from 1900 to 2000 and limits the maximum distance affected by recurrent hypoxia in the Bight.

METHODS

RECALCULATION OF HISTORICAL CORE-TOP DATA

Published foraminifer census data were recalculated to determine the hypoxia proxy, the *Ammonia* to *Elphidium* (A/E) index (Sen Gupta and others, 1996), in 267 core-top samples from the Mississippi Bight (Fig. 2). The core tops, which were recovered in 1951 to 1956, consisted of the top 1 cm of sediment (~10 ml) from Phleger-type gravity cores. All were sieved on a screen of 74 μm openings. The census data included that of Phleger (1954, 1955), Parker (1954) and Lankford (1959). Phleger (1954) cautioned that some of his samples may have suffered post-collection dissolution. The A/E index was calculated as 100 times the number of specimens of *Ammonia* (*A. parkinsoniana* (d'Orbigny) plus *A. tepida* (Cushman)) divided by the number of specimens of *Ammonia* plus all members of the *Elphidium gunteri* Cole - *E. excavatum* (Terquem) plexus. The number of specimens counted was not reported in the 1950's studies, so the minimum number counted was estimated from the reported foraminiferal number, assuming that splits to ~300 specimens were made of all samples reporting >500 foraminifers per 10 ml of wet sediment. Samples were accepted for mapping if they contained ≥20 specimens of *Elphidium* plus *Ammonia*. Twenty specimens are adequate to distinguish hypoxic samples (A/E > 80%) from clearly oxic samples (A/E <50%; Patterson and Fishbein, 1989). The A/E index is effective at inner shelf depths <30 m (Platon and Sen Gupta, 2001).

A second proxy of hypoxia was calculated from the combined relative frequency of three hypoxia-tolerant species, *Pseudononion atlanticum* (Cushman), *Epistominella vitrea* Parker and *Buliminella morgani* Andersen (the PEB index of Osterman and others, 2001, and Osterman, 2003). Assumptions similar to those made for the A/E index were made for species abundance in the PEB index. Note that Osterman (2003) used the >125 μm fraction, whereas the 1950's studies use the >74 μm fraction. The PEB index is effective in mid-shelf depths >30 m.

ANALYSIS OF GRAVITY CORES

Cores and data collected during the Northern Gulf Littoral Initiative (Sawyer and others, 2001) were used in this part of our project. Two gravity cores were collected in different seasons from a single site in 60 m of water and 44 km east northeast of Pass à Loutre of the Mississippi River delta (Fig. 2, Table 1). The coring site was selected principally because hypoxia was noted by a direct measurement in bottom waters in September of 2000, but it must be noted that the calibration of this sensor was problematic (C. Szczechowski, written communication, 2005). Low oxygen, but not hypoxia, was reported by SEAMAP on the outer shelf a few kilometers seaward of this site in September of 2000.

The cores were assessed using various non-destructive methods. The cores were X-rayed and logged for sound speed and wet bulk density at the Naval Research Laboratory (NRL), Stennis Space Center, using a GEOTEK Multi-Sensor Core Logger. Magnetic susceptibility was measured at the University of New Orleans Department of Geology and Geophysics. Following these analyses, the split cores were digitally photographed and visually described in preparation for sampling. These data were used to correlate the cores.

^{210}Pb and ^{137}Cs activities were used to date the top 55 cm of core 500C-3. X-radiographs indicated that sediments from the top 55 cm appeared suitable for dating in that they appeared bioturbated to some degree with some primary stratification remaining intact. Further, the X-radiographs showed no evidence of disturbance due to coring. Activities of ^{210}Pb and ^{137}Cs were measured via gamma spectrometry (Cutshall and others, 1983) on 1-cm slices spaced at 3-cm intervals in the top 10 cm of the core and 5-cm intervals from 10 to 55 cm. A biodiffusion coefficient and apparent accumulation rate were calculated following Nittrouer and others (1984) and Bentley and Nittrouer (2003) in order to determine the degree of bioturbational mixing and attenuation that an assemblage caused by an hypoxic event might undergo.

Analysis of Foraminifers

Foraminifers were sampled and prepared from core TMGC-19. One half of the top 20 cm of the core was sliced into 1-cm-thick slabs, each slab covering ~5 years of deposition based on the age model. The slabs were weighed wet, dried in an oven at 50°C, disaggregated in a 1% Calgon solution, and sieved on a screen with 63 μm openings to remove silt- and clay-size particles. The sand-size residue was dried in preparation for microscopic inspection. A

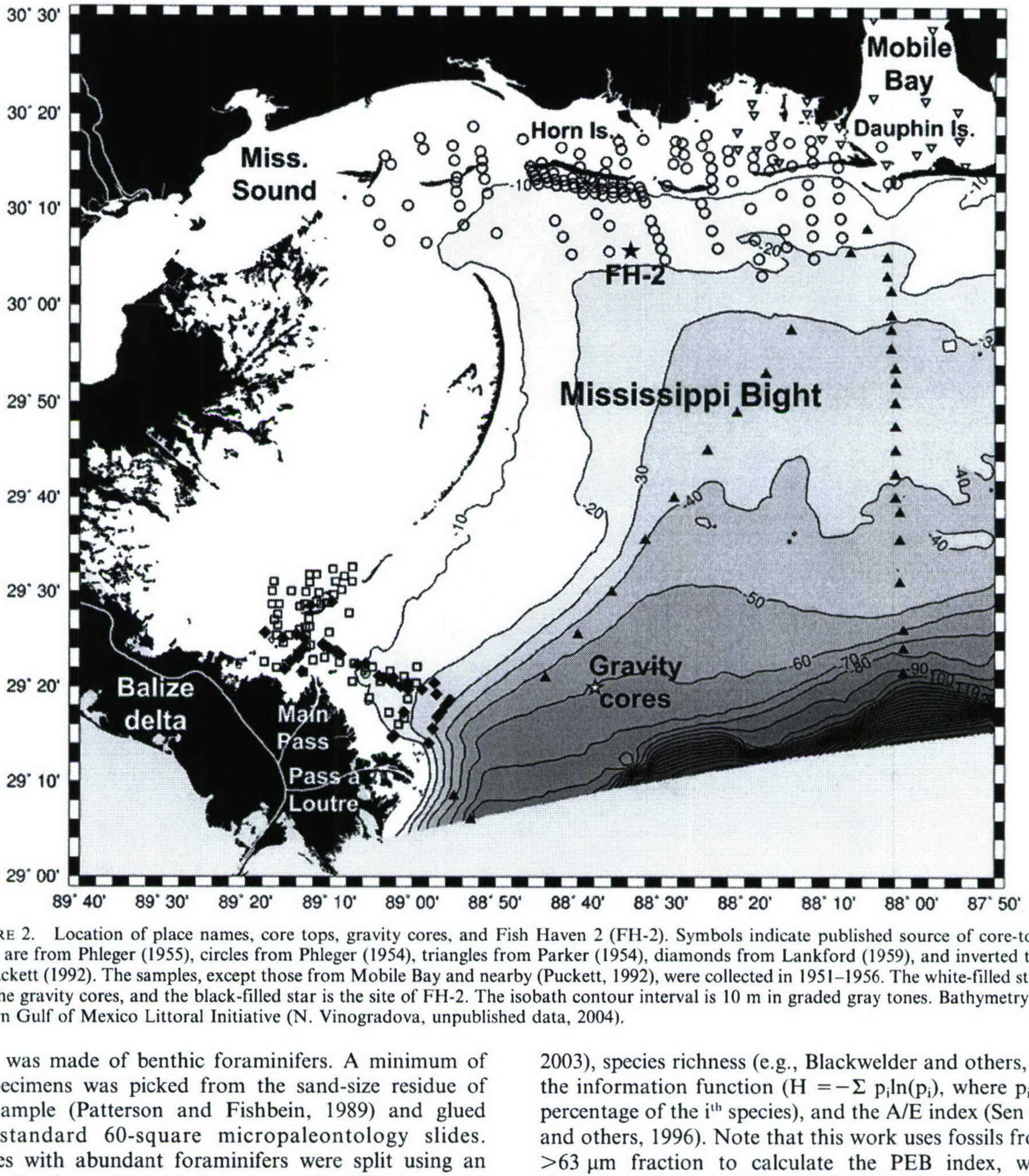

FIGURE 2. Location of place names, core tops, gravity cores, and Fish Haven 2 (FH-2). Symbols indicate published source of core-top data. Squares are from Phleger (1955), circles from Phleger (1954), triangles from Parker (1954), diamonds from Lankford (1959), and inverted triangles from Puckett (1992). The samples, except those from Mobile Bay and nearby (Puckett, 1992), were collected in 1951–1956. The white-filled star is the site of the gravity cores, and the black-filled star is the site of FH-2. The isobath contour interval is 10 m in graded gray tones. Bathymetry is from Northern Gulf of Mexico Littoral Initiative (N. Vinogradova, unpublished data, 2004).

census was made of benthic foraminifers. A minimum of 300 specimens was picked from the sand-size residue of each sample (Patterson and Fishbein, 1989) and glued onto standard 60-square micropaleontology slides. Samples with abundant foraminifers were split using an Otto-style microsplitter. Each test was identified to species or genus following the classification of Loeblich and Tappan (1987) and using the Micropaleontology Press online Catalogue of Foraminifera, initially complied by Ellis and Messina (1940). Taxonomic notes are available in Maclean (2002).

Several proxies of hypoxia were calculated from the census data, including the PEB index (e.g., Osterman, 2003), species richness (e.g., Blackwelder and others, 1996), the information function ($H = -\Sigma\ p_i \ln(p_i)$, where p_i is the percentage of the i^{th} species), and the A/E index (Sen Gupta and others, 1996). Note that this work uses fossils from the >63 μm fraction to calculate the PEB index, whereas Osterman (2003) used the >125 μm fraction.

Analysis of Framboidal Pyrite

The sampling scheme for framboidal pyrite analysis mirrored that used for foraminiferal analysis. The top 20 cm of the second half of core TMGC-19 was sliced into 1-cm-thick slabs, each covering ~5 years of deposition. The

TABLE 1. Description of gravity cores.

Core Name	Collection Date	Vessel (R/V)	Latitude (°N)	Longitude (°W)	Water Depth (m)	Core Length (cm)
500C-3	May 2000	*Pelican*	29° 19.396′	88° 38.106′	59.1	266
TMGC-19	Sept. 2000	*Tommy Munro*	29° 19.983′	88° 37.971′	60.5	219

slabs were prepared wet in order to preserve framboid structure and morphology. The wet sediment was homogenized, and a small aliquot was dispersed into 25 ml of the heavy liquid lithium heteropolytungstate (LST, density =2.85 g/ml), and rinsed on a filter of 1-µm openings to remove salt. The washed sediment was combined with 50 ml of LST and centrifuged for 30 minutes at 3,000 rpm. The heavy fraction was flash-frozen by partial immersion in liquid nitrogen, and the light fraction was decanted. The heavy fraction, containing framboidal pyrite, was poured onto a filter of 1-µm-diameter pores, rinsed thoroughly with distilled water, and dried. The filter was glued to a silica plate for stability, and carbon coated for scanning electron microscopy (SEM).

All samples were examined by SEM to assess the number and size of pyrite framboids throughout the upper 20 cm of the core. For each sample, nine random areas were captured digitally in a field of view at 800× (0.1 mm^2) using backscattered electrons. Each field of view was assessed in an image-processing program (USTHSCSA Image Tool version 2.0) to determine the area and perimeter of each framboid. Only framboids that occurred as free spheres were measured. The effective diameter (D_{eff}) of each framboid was calculated from this equation:

$$D_{eff} = \sqrt{\frac{4 \times \text{Area}}{\pi}}$$

Adjacent 2-cm intervals were combined to increase the number of framboids measured per sample.

RESULTS

AGE MODEL AND TEMPORAL RESOLUTION FOR GRAVITY CORES

In order to estimate sedimentation rates and the influence of bioturbation on the temporal resolution of our core data, we fitted the excess ^{210}Pb distribution of core 500C-3 to end-member steady-state solutions of the advection-diffusion-reaction equation. Results of this analysis allow us to further assess the influence of bioturbation on the mixing and destruction of individual sediment layers using the event layer bioturbation model of Bentley and Sheremet (2003). Following the approach of Nittrouer and others (1979), we assume that bioturbation and radioactive decay may be the dominant processes influencing excess ^{210}Pb distributions in sediments near the sediment-water interface, and that sediment burial and radioactive decay are the dominant processes below the depth of bioturbation (L_b). We suggest that the depth of bioturbation is ~7 cm, based on the maximum depth of ^{137}Cs and an inflection point in the ^{210}Pb profile (Fig. 3). Fitting the ^{210}Pb data below the 7 cm depth to a steady state model of sediment accumulation and radioactive decay (Nittrouer and others, 1979; Bentley and Nittrouer, 2003) yields an apparent accumulation rate (S; cm/y) in gravity core 500C-3 of 0.2 cm/y. Similarly, fitting ^{210}Pb data above the 7 cm depth to a steady state model of biodiffusion and radioactive decay yields a biodiffusion coefficient D_b of 2.4 cm^2/y (Nittrouer and others, 1979; Bentley and Nittrouer, 2003).

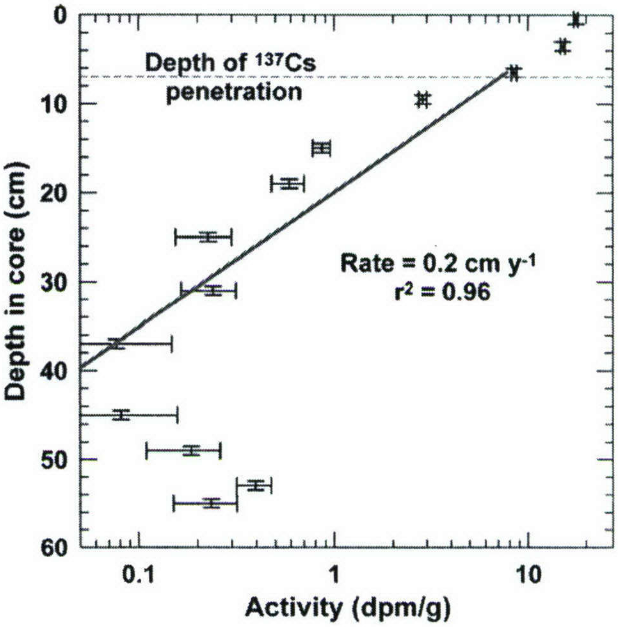

FIGURE 3. Sedimentation rate (solid gray line) determined from excess ^{210}Pb activity in core 500C-3. The depth of the mixed layer is determined by the depth of penetration of ^{137}Ce (dashed gray line) and the upper inflection point of excess ^{210}Pb activity.

The model of Bentley and Sheremet (2003) predicts the degree to which a layer of sediment will be disrupted (and mixed with adjacent sediments) by bioturbation as that layer is buried by continued sedimentation. Necessary parameters include the initial layer thickness L_s (cm), background accumulation rate (0.2 cm/y), bioturbation depth (7 cm), and the distribution of bioturbation intensity versus depth (α_z;1/y, a first-order rate constant). The value of α_0 can be estimated by $\alpha_0 \sim 2D_b/L_b^2$. If the intensity of bioturbation decreases exponentially with depth, α_z can be estimated from $\alpha_z = \alpha_0 \exp(-\beta z)$, where the value of β (1/cm) is estimated from field or laboratory observations. No data exist that allow us to estimate β for our study area; however, we can hypothesize that either α (7 cm) ~ α_0 (i.e., $\beta = 0$), or that α (7 cm) $\ll \alpha_0$ (for example, $\beta = 0.5$). For a sediment layer 1 cm thick (such as a relatively thick layer of flood sediment), buried at 0.2 cm/y, the final degree of layer preservation is 3–50%, depending on the depth-distribution of bioturbation. In other words, 50–97% of the original sediment layer is disrupted by bioturbation and potentially mixed with adjacent sediments. For a thinner layer of 0.017 cm (~ one month of steady-state sedimentation at 0.2 cm/y, the length of some seasonal hypoxia events), the final degree of layer preservation is 3–38% for the above range of β values, suggesting that reworking of some sediment from one depth interval to the next is likely under most conditions. The *maximum* age difference between particles mixed from adjacent layers is equal to the transit time through the zone of bioturbation (Wheatcroft, 1990), which is L_b/S = 7 cm/0.2 cm/y = 35 y. However, the presence of recognizable sediment layers

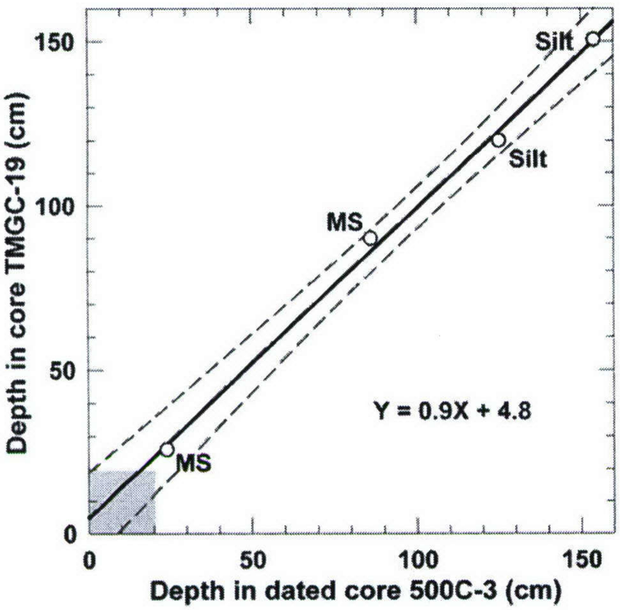

FIGURE 4. Graphic correlation of ^{210}Pb-dated core 500C-3 to TMGC-19. The solid black line is the regression model and the gray dashed lines mark the 95% confidence interval. MS = tie point using a distinctive change in magnetic susceptibility. Silt = tie point made using a distinctive silt layer. Gray-shaded box indicates interval (0–20 cm) sampled for this study. The cores match one-to-one within the limits of the 95% confidence interval.

and magnetic signatures in our gravity cores suggests that vertical mixing is not so intense, and that significant depositional stratigraphy is preserved in these cores. Thus, temporal resolution is probably much finer than the transit time of 35 y.

It is reasonable to assume that the accumulation rates of cores TMGC-19 and 500C-3 are the same in the upper 20 cm and that the age model of core 500C-3 can be applied one-to-one to core TMGC-19, because they are sampled from the same location and they are identical in appearance and physical properties. The assumption was tested by graphic correlation. Two distinctive silt layers and two distinctive changes in magnetic susceptibility were used as tie points between the cores. The regression through the points (Fig. 4) has a slope of 0.94, which is not significantly different from 1 at a 95% confidence interval, and an extrapolated Y intercept of 4.8 cm, which is also not significantly different from zero at a 95% confidence interval. Unfortunately, the regression model is flawed by extrapolation because all four tie-points lie below the sampled interval. With this caveat in mind, we proceed with the assumptions that the two cores correlate one-to-one and that the age model of Core 500C-3 can be applied directly to TMGC-19.

Age of the Core Tops

The core tops were taken in 1951–1956 (Parker, 1954; Phleger, 1954 and 1955; Lankford, 1959). Core tops taken from the modern, prograding muds of the Balize delta are probably no worse in resolution than the gravity core described above, so the samples at worst include some fossils mixed in from the 1940's as well as those from the early 1950's. In contrast, samples from the central and northern Bight are taken from a disconformable surface of muds and sands reworked from the underlying late Holocene highstand deltas (Brooks and others, 1995; Kulp and others, 2002), which downlap eastward onto the early Holocene transgressive sand sheet (Anderson and others, 1997). Recent sediments are ephemeral in this area, so modern foraminifers are mixed with fossils from underlying units and temporal resolution is poor.

Hypoxia Indicators

Foraminifers in the Core Tops

Results of 267 core-top samples (Fig. 5) show apparent recurrent hypoxia in the 1940's–1950's in the offshore between Pass à Loutre and Main Pass, where the A/E index exceeds 90%. The ratio is high in a coherent pattern, which includes the data of all three workers (Parker, 1954; Phleger, 1955; Lankford, 1959). The hypoxia extends eastward at least 16 km in the early 1950's, based on the proxy. The A/E index is >90% at two locales south of the Mississippi-Alabama barrier islands: one south of Horn Island and one south of Dauphin Island. In the central Mississippi Bight, the PEB index was plotted to assess hypoxia in waters deeper than 30 m. The index remains below 25% in the middle Bight east of ~88° 50′ and south of 30°N, suggesting oxygenated bottom water (Fig. 6).

Foraminifers in the Gravity Core

The foraminiferal assemblage from the gravity core in the middle Mississippi Bight is both diverse and moderately equitable. Overall, *Epistominella vitrea* Parker and *Rosalina subaraucana* (Cushman) are the most abundant species, comprising 11 and 9% of the assemblage, respectively. *Hanzawaia strattoni* (Applin), *Stetsonia minuta* Parker, *Globocassidulina* cf. *G. subglobosa* (Brady), *Pseudononion atlanticum* (Cushman), *Brizalina lowmani* (Phleger and Parker), *Cibicides pseudoungeriana* (Cushman), *Rotorbinella basilica* Bandy and *Buliminella morgani* Andersen are common, each averaging 3–8% of the assemblage (Maclean, 2002). Diversity (S) averages 52 species per sample and accumulates to >138 species overall, and the information function (H) averages 3.24. None of these measures changed significantly over the past century (Fig. 7), and all of these values are consistent with assemblages from oxygenated bottom water. In comparison, both diversity and H are significantly reduced in the "dead zone" of the Louisiana shelf (Blackwelder and others, 1996; Osterman, 2003; Platon and others, 2005).

The PEB index (Blackwelder and others, 1996; Osterman, 2003) averaged 19% of the assemblage throughout the last 100 years. Values from 1935, 1930 and 1925 are significantly lower than the mean value at a 95% confidence interval, but older and younger periods are not significantly different from the mean. In contrast, values of PEB from the "dead zone" on the Louisiana shelf generally exceed 20% and reach values as high as 53% since 1960 (Osterman, 2003; Osterman and others, 2005). Finally, the A/E index averaged 20% over the last century, and never

FIGURE 5. *Ammonia* to *Elphidium* index of oxygenation. Values above ~75% suggest recurrent, seasonal hypoxia in the 1950's, when the core tops were collected. Notice high values centered seaward of Dauphin Island and Horn Island of Mississippi Sound, and east of Main Pass and Pass à Loutre. Circles are from Phleger (1954), squares from Phleger (1955), triangles from Parker (1954), and diamonds from Lankford (1959). For comparison, the data of Puckett (1992) are plotted as inverted triangles in the Mobile Bay area, which is known for its seasonal hypoxia. Notice the locations of FH-2 (black-filled star) and the gravity cores (white-filled star). Radius of masking circles is 10 km.

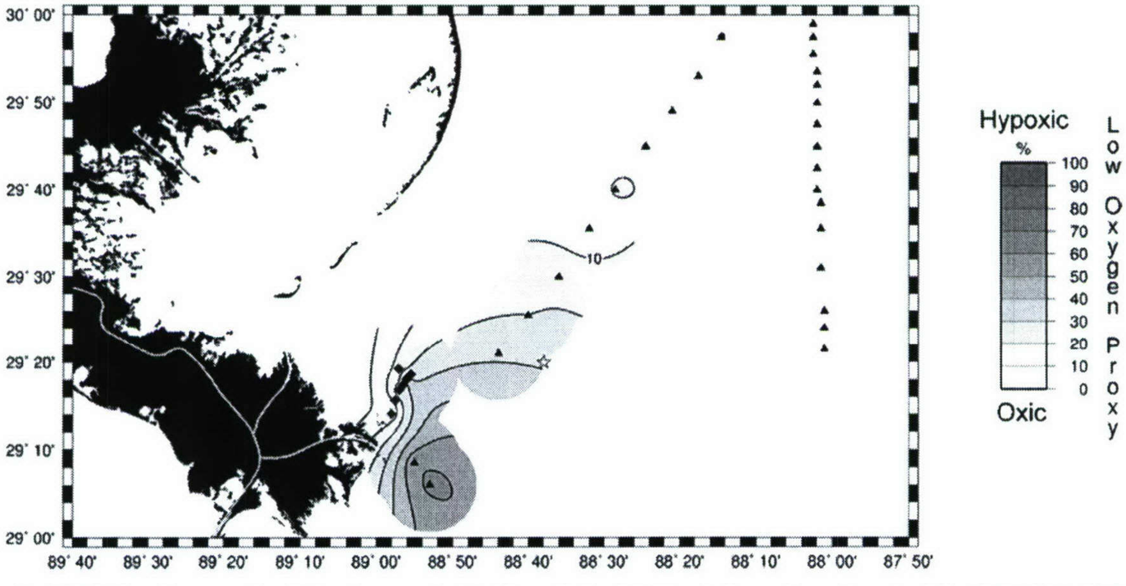

FIGURE 6. PEB index of oxygenation. Triangles are calculated from Parker (1954) and diamonds are from Lankford (1959). Black-filled star is FH-2 and white-filled star marks the gravity cores. The PEB index is effective in shelf depths >30 m. Large values suggest low oxygen. Notice that values are low throughout most of the deep Mississippi Bight, except for two samples at 50 and 80 m off Pass à Loutre. The deeper Bight appears well oxygenated in the 1950's. Masking circles are 10 km in radius.

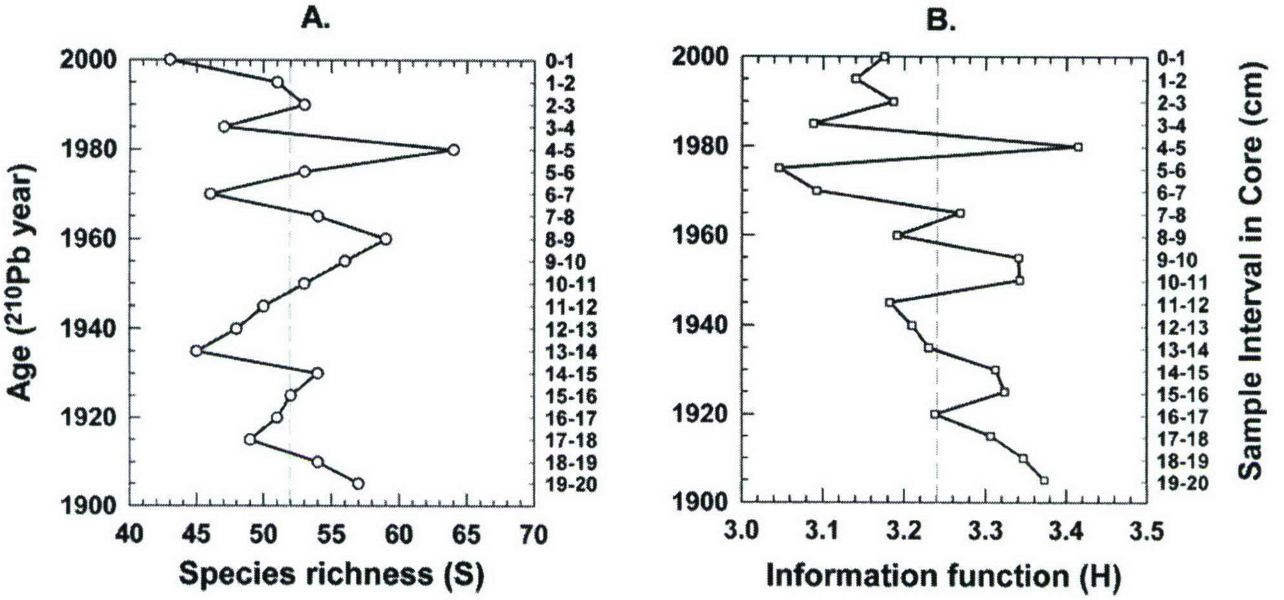

FIGURE 7. A. Species richness; B. Information function. Neither species richness (S) nor the information function (H) decreases significantly up-core. Vertical dashed lines mark the means.

exceeded 35%. However, interpretation of the A/E proxy should be regarded with caution at this depth in the Mississippi Bight because the proxy is highly variable at depths greater than 30 m in the Louisiana Bight, where the two species are reduced in frequency (Platon and Sen Gupta, 2001). All of these results lead to a similar conclusion, that oxygenation at this site was apparently good throughout each 5-year interval of the past 100 years (Fig. 8).

It is reasonable to ask if bioturbation at the core site could mix an hypoxia assemblage beyond the point of recognition. Specifically, modeling of ^{210}Pb parameters at our core site in the Mississippi Bight suggests preservation of 3–38% of a layer deposited during a one-month period (Bentley and Sheremet, 2003), which is the known duration of the one hypoxic event that was monitored throughout its development at FH-2 in 2004. The probability of preservation of an hypoxia assemblage is enhanced if events persist for multiple months and recur in succeeding years, as they do in the Louisisana Bight, where production of normal foraminifer faunas appears to be curtailed in the "dead zone." However, events at the gravity core site in the deep

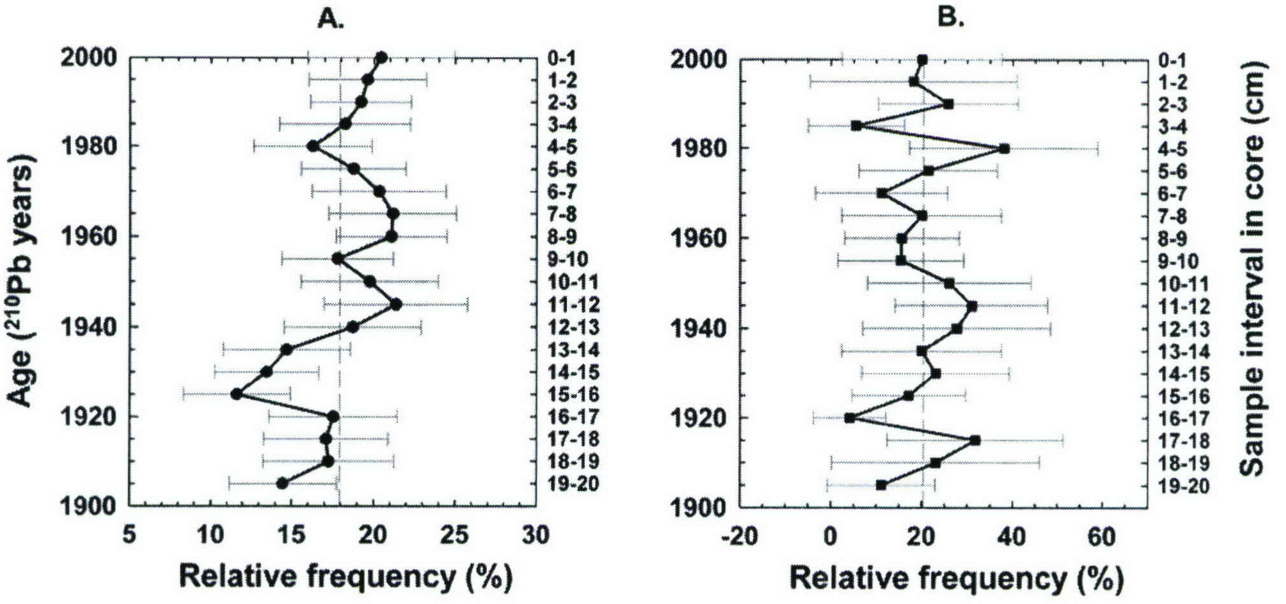

FIGURE 8. A. PEB index; B. A/E index. Hypoxia proxies show no significant trend up-section in core TMGC-19. Error bars are for 95% confidence interval for sampling error (Patterson and Fishbein, 1989). The error associated with the A/E index is larger than that for the PEB index because the number of specimens (n) is less. The vertical dashed lines mark the means.

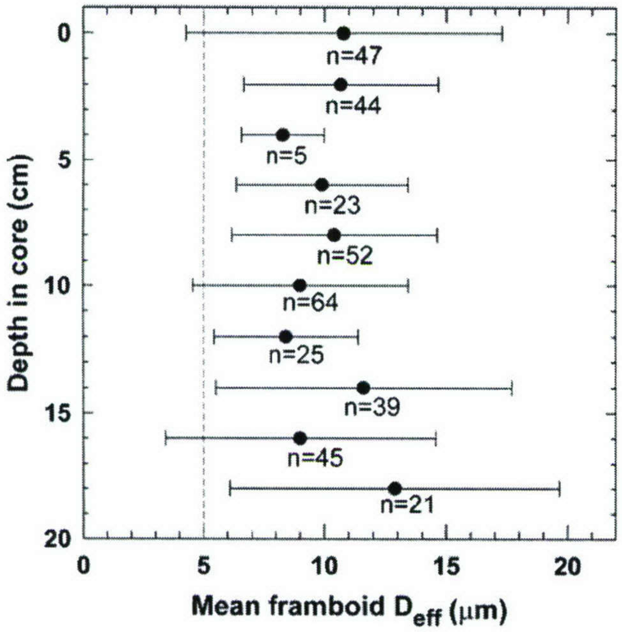

FIGURE 9. Average diameter and sample standard deviation of pyrite framboids. The number of framboids measured is indicated by n. Framboids < 5 mm form in the water column, suggesting anoxia, whereas those > 5 mm (dashed line) form in the sediment, suggesting oxygenated bottom water.

Mississippi Bight (>30 m) appear to be shorter in duration and may not recur annually. Production of normal assemblages may not be curtailed throughout the entire summer nor from year to year. Even if, optimistically, 38% of a one-month hypoxic layer is intact (Bentley and Sheremet, 2003), such a layer may be difficult to recognize due to admixture with the normal assemblage.

Framboidal Pyrite

Framboid size distributions are similar in all gravity core samples. The mean effective diameter (D_{eff}) ranges from 8 μm to 13 μm and does not change significantly with depth in the core (Fig. 9). Framboids $\leq$5 μm in diameter occur in modest frequencies (10%–25%) in three combined periods, 1955 and 1950 (n= 64), 1945 and 1940 (n= 25), and 1930 and 1925 (n= 45), but the variability in size remains high in all samples. The results are consistent with formation of framboids in the sediment rather than in an anoxic water column (Wilkin and others, 1996; Wilkin and Barnes, 1997a, b). Alternatively, if there was anoxia in the bottom water at this site at times over the past 100 years, then the signature of small framboids was mixed beyond recognition.

DISCUSSION

Results from the core-top data, which sample the 1940's–1950's, suggest that recurrent, seasonal hypoxia apparently occurs in the Mississippi Bight. Hotspots front the eastern passes of the Mississippi River, extending from at least the 10-m isobath to16 km offshore from Pass à Loutre, the distance of the most eastward hypoxic sample. Recurrent, seasonal hypoxia appears to plague two locales seaward of the Mississippi-Alabama barrier islands, one south of Horn Island and one south of Dauphin Island. In contrast, all evidence points to predominantly oxygenated conditions on the seafloor >30 m in the central Mississippi Bight, based both on core tops, which recorded the 1940's–1950's, and the gravity core, which recorded the history of the past century in increments of 5 years.

Reports of bottom-water oxygen provide inconclusive validation of the foraminiferal results that suggest recurrent hypoxia. The SEAMAP environmental data are discrete measurements, sampling a single moment at each of its sites once or, rarely, twice during the summer months. The frequency, duration and development of hypoxia cannot be assessed with such data, and an oxic result at a site does not preclude hypoxia at another time in the summer. However, the data do occasionally sample low-oxygen to hypoxic conditions in the Mississippi Bight over the past two decades of data collection, and the hypoxic events tend to cluster offshore of the passes from the Balize delta and the Mississippi Sound, as well as along the shelf edge. At present, no continuous time series of bottom oxygen is available. The State of Mississippi Department of Marine Resources (DMR) conducted monthly measurements in 2003–2004 at two stations in Fish Haven 2 (FH-2) at 20 m water depth. FH-2 lies within the hypoxic hotspot south of Horn Island indicated by the A/E index. The DMR data confirm a month-long period of hypoxia at the site in August, 2004 (Joe Jewell, written communication, 2004).

It is possible that the A/E index responds only indirectly to oxygenation and directly to other variables that correlate to oxygen. Any condition that favors the bacteria-eating generalist *Ammonia* (Goldstein and Corliss, 1994) over the fresh-diatom-consuming *Elphidium* (Gustafsson, 1999) will increase the A/E index. For example, shading due to recent increases in turbidity might explain the increase in the index in Long Island Sound (E. Thomas, oral communication, 2004). In the Mississippi Bight, suspended sediments with associated organic matter and bacteria are delivered to the Mississippi Bight by deposition from sediment-laden plumes and bedload transport (McKee and others, 2004) and can form nepheloid layers. Fluid mud also can form layers of mobile sediment on the seafloor that can be associated with low oxygen and hypoxia (Aller, 1998). Such material is repeatedly resuspended and transported by currents that are driven by waves, tides and gravity (Coleman and others, 1998; Friedrichs and others, 2000; Wright and others, 2001) above the regional, relict surface seaward of the Mississippi-Alabama barrier islands (Brooks and others, 1995; Kulp and others, 2002) and above the prograding prodelta of the modern Balize delta (Coleman and others, 1998; McKee and others, 2004). The material is transported episodically, consuming pore-water oxygen until the material ultimately reaches a long-term depocenter (Rotondo and Bentley, 2003; McKee and others, 2004). Anecdotal reports place turbid bottom water and ephemeral layers in the Mississippi Bight (Captain Monty Simmons, oral communication, 2004). The turbidity events could impose differential stresses on benthic species by facilitating bacterial consumption of labile organic matter, including fresh diatoms; exacerbating oxygen depletion; promoting substrate instability; and shading benthic flora. Such conditions could favor *Ammonia* over *Elphidium* in the areas of high A/E values near the passes from Mississippi Sound and the Balize delta. The possibility is an interesting avenue for future investigation.

CONCLUSIONS

Several apparent hotspots of low oxygen to hypoxia were identified by foraminiferal indices of hypoxia, the A/E index (Sen Gupta and others, 1996) and the PEB index (Blackwelder and others, 1996; Osterman, 2003). The hotspots are in water depths less than 25 m: one lies on the Balize prodelta between Pass à Loutre and Main Pass; and the other two are seaward of Horn and Dauphin islands of the Mississippi-Alabama barrier islands. The hotspots were identified in core tops collected in the 1950's and are partially validated by present-day, summertime measurements of bottom-water oxygen. In contrast, the Mississippi Bight waters deeper than 30 m apparently remained well oxygenated in the 1950's. Results based on two independent lines of evidence, the PEB index and pyrite framboid size distribution, from a well-dated gravity core confirm predominantly good oxygenation over the past century at the site, which lies in 60 m of water and 44 km distant from Pass à Loutre. This result constrains the maximum seaward extent of apparent hypoxia at the Pass à Loutre and Main Pass hotspot.

Questions are raised concerning the direct response of index species to oxygenation. It is possible that the species respond indirectly to low oxygen and directly to variables that correlate with low oxygen.

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