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14. ABSTRACT

Abstract—The effects of hypoxia on benthic community structure and processes are well documented but the direct and indirect effects of hypoxia on seafloor properties are unknown. Using bottom oxygen data compiled by Louisiana Universities Marine Consortium, we chose four provinces with sea floors having different number of annual exposures to hypoxia from 1985 to 2006. The provinces were arrayed east to west along the 30-m depth contour from the Mississippi River bird's foot (FH), to south of Terrebonne Bay (BH), and to south of Atchafalaya Bay (HO and NO). Several sediment properties can be affected as

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Effects of Hypoxia on Sediment Properties in the Northern Gulf of Mexico

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Abstract—**The effects of hypoxia on benthic community structure and processes are well documented but the direct and indirect effects of hypoxia on seafloor properties are unknown. Using bottom oxygen data compiled by Louisiana Universities Marine Consortium, we chose four provinces with sea floors having different number of annual exposures to hypoxia from 1985 to 2006. The provinces were arrayed east to west along the 30-m depth contour from the Mississippi River bird's foot (FH), to south of Terrebonne Bay (BH), and to south of Atchafalaya Bay (HO and NO). Several sediment properties can be affected as a consequence of the vertical zonation and diversity differences between benthos living in hypoxic and normoxic areas. Sediment physical and acoustic properties were measured on cores collected from the March/April 2009 cruise to attain baseline values for comparison among provinces and between pre-hypoxic and persistently hypoxic provinces to be sampled in early September 2009, August 2010, and July 2011. Average values for sediment compressional wave velocity ratio were 1.063, 1.003, 0.979, and 0.995 for provinces NO, BH, FH, and HO, respectively. Average values for sediment compressional wave attenuation were 0.93, 0.30, 0.11, and 0.32 dB/m•kHz for provinces NO, BH, FH, and HO, respectively. Average values for sediment shear strength in the uppermost 5 cm of subcores were 1.3, 1.8, 0.6, and 0.8 kPa for provinces NO, BH, FH, and HO, respectively. The gradients of sediment shear strength in the top 5 cm of sediment were 0.40, 0.42, 0.17, and 0.28 kPa/cm for provinces NO, BH, FH, and HO, respectively. Sediment grain size distribution and bulk density were measured at 1-cm intervals in the top 2 cm of the core and at 2-cm intervals below those increments on 22 cores. The sediments at provinces NO, BH, and HO were very poorly sorted to extremely poorly sorted sand-silt-clays (mean: 4.9, 8.3, and 8.1 phi, respectively); the sediment at the FH province was a very poorly sorted silty clay (mean: 11.1). Average values for sediment density were 1.819, 1.597, 1.289, and 1.519 g/cm^3 for provinces NO, BH, FH, and HO, respectively. Sediment permeability was measured from each of the 24 box cores on 13-cm-long cores with a falling head permeameter.**

I. Introduction

Occurrence of hypoxia in coastal areas is rapidly increasing globally. The occurrence of low oxygen stress events affects the benthic community and thus the physical and geological processes occurring in inner continental shelf and estuarine sediment deposits, including permeability, erodibility, porosity and shear strength. The effects of differences in sediment porosity and permeability as a consequence of hypoxia may affect acoustic properties in a predictable way. The effects of hypoxia on benthic community structure (biomass, diversity, density, distribution, organism size, and function, etc.) and processes (rates and depth of bioturbation, biochemical zonation, and productivity, etc.) are well documented but the direct and indirect effects of hypoxia on seafloor properties are unknown.

The locus of the transformation of sediment properties via bioturbation is the sediment-water interface, where the majority of benthos lives and affects gradients by burrowing. The presence of vertical gradients in physical properties at the sediment-water interface is a well documented fact in all sand and mud sediments [1]. Such gradients are a function of the physical nature of the sediments and the activities of the biological community colonizing the interface [2]-[4]. The establishment of the gradients in sediment porosity, density, and permeability controls acoustic scattering, propagation, and bottom loss, as well as rates of subsidence or compaction due to dewatering.

Empirical data has presented a number of compelling cases that motivate an investigation into the consequences of naturally occurring stress events disrupting the maintenance of physical property gradients and the eventual re-establishment of gradients. Among the motivating cases:

- Catastrophic decimation and recovery of benthic community from Hurricane Ivan during SAX04 results in loose-packed sands dewatering and compacting over a six-week period [5],[6].
- Strong tidal currents in St. Andrew Bay Channel, Panama City, Florida and Rebecca Shoal, Lower Florida Keys limit the numbers and type of benthic fauna living in high-stress regime and result in loose-packed sands with open structure that promotes high permeability [7].
- Vertical burrows from benthic fauna in storm deposits off the Eel River increase the permeability of silty sediments by 2-3 orders of magnitude [8].
- Seasonal hypoxia in the northern Gulf of Mexico brought on by eutrophication changes the naturally occurring benthic community from *K*-selected equilibrium populations to *r*-selected high density pioneering populations [9]-[16] and may result in dramatic changes in physical properties of the sediment-water interface.

Documentation of the change in sediment porosity from Hurricane Ivan indicates nearly a 1% average decrease due to re-establishment of gradients by colonizing infauna. The porosity decrease occurred within the top 14 cm and decreases

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varied from -1.9% within the top 2 cm of sediment to -0.3% deeper in the sediment. In the Eel River study, flood deposits smothered the existing benthic community creating a "death assemblage" 4-14 cm below the recently deposited mud. Those buried sediments that contained vertical burrows had measured permeability values up to three orders of magnitude higher than the values measured in the overlying storm deposits of the same grain size. On the northern Gulf of Mexico inner shelf (29-60 m water depth), stratification of water masses and a high input of organic matter resulting from eutrophication promote the development of the second largest zone of coastal hypoxia in the world [17]. Hypoxia is defined as a low-oxygen condition (O_2< 2 mg/l) that produces severe environmental stress in many organisms and has been documented in over 43 locations in the world's oceans [18]. Density stratification is initiated from the freshwater discharged by the Mississippi and Atchafalaya Rivers and eutrophication is promoted from seasonal inputs of nitrogen believed to be derived from fertilizer runoff in the Mississippi River System.

The presence of hypoxic zones on the shelf off Louisiana has been demonstrated to reoccur seasonally. Though the hypoxia does not persist through the fall and winter months, the spatial and temporal extent of the hypoxia has been demonstrated to vary from year to year. This means that some areas are exposed to hypoxia for different time periods and this creates a natural exposure gradient in which hypoxic conditions can affect benthic communities and sediment properties. Areas of high deposition (organics and sediment) and low oxygen are colonized by a few organisms that are restricted to the sediment surface. These organisms concentrated in the uppermost region of the sediment column are the pioneering stage of benthic succession [9],[19],[20]. The benthic community remains at that stage as long as the low-oxygen conditions raise the depth of the redox potential discontinuity (RPD) to near-surface sediment depths. In contrast, well oxygenated areas have developed diverse benthic communities that have attained the equilibrium stage of succession, which include larger, deeper burrowing fauna. The diverse, deeper-burrowing benthos helps to create a deeper RPD.

As a consequence of the vertical zonation and diversity differences between stressed and recovered areas, several sediment properties are affected:

- **Permeability**: well oxygenated, burrow-filled areas should have higher permeability than hypoxic areas.
- **Porosity**: areas of high sediment and organic deposition tend to have higher porosity (lower bulk density) in the hypoxia-affected surficial sediments than sediments lying below well oxygenated water. High porosity (low density) sediments.
- **Erodibility**: fluffy, uncompacted sediments in hypoxic zones can easily be transformed into fluid mud under the action of surface gravity waves reducing significant wave heights, increasing turbidity, and decreasing visibility. However, the presence of dense mats of surface dwelling pioneering fauna in hypoxic areas should tend to stabilize sediments and armor the sea bed from (non-catastrophic) sediment resuspension events.
- **Shear strength**: areas of high sediment and organic deposition should have lower shear strength in the affected zone of the surficial sediments than sediments lying below well oxygenated water, except in those cases where pioneering fauna create dense surficial mats.
- **Acoustic properties**: as a consequence of the differences in permeability and porosity, sediment sound speed and attenuation are affected such that muddy areas of higher porosity (hypoxic zones) should have lower sound speed and attenuation than muddy areas of lower porosity (oxygenated zones). Despite the contrary effects of lower permeability in the hypoxic zones, the sediment rigidity should have a larger effect on the acoustic properties.

II. Methodology

Using bottom oxygen data compiled by Nancy Rabalais at the Louisiana Universities Marine Consortium, we chose four provinces with sea floors having different number of annual exposures to hypoxia from 1985 to 2006. The normoxic province (NO) had a frequency of hypoxia occurrence of less than 25%; the briefly hypoxic province (BH), the frequently hypoxic (FH) and hypoxic (HO) provinces had a frequency of hypoxia occurrence of greater than 25%, but varied in terms of their recent history of seasonal hypoxia. The provinces were arrayed east to west at 30- to 40-m water depths from near the Mississippi River bird's foot (FH), to south of Terrebonne Bay (BH), and to south of Atchafalaya Bay (HO and NO). Furthermore, these provinces represent environments in which hypoxia is water-column driven (FH), benthos-driven (HO), and transitional between the two environments (BH) in the sense of the model described by Hetland and DiMarco [21]. Our approach is to collect baseline data from these four provinces in the spring in advance of the seasonal hypoxia that will develop in the summer of 2009, then return to collect duplicate data in late summer 2009 (September), 2010 (August), and 2011 to document the change in surficial sediment properties.

Data Collection and Analysis

Sediments from all four provinces were sampled with a 0.25-m^2-area box corer, photographed with a Sediment Profile Imaging camera, and surveyed with an Acoustic Sediment Classification Sonar.

Box Cores: Six box cores were collected from each of the four provinces with the box corer. The sampling design consisted of three stations separated by one kilometer as vertices of a triangle centered at the province location (Fig. 1). From each of the three stations, two box cores designated 'A' and 'B' were collected. Province NO differed from this scenario, such that three box cores ('A', 'B', and 'C') each were collected from the center of the province and from the lower right vertex of the triangle. From each of the 24 box cores a variety of cores were collected as subcores:

1) Physical, Chemical, and Acoustic (PCA) Property Subcores: Three 5.9-cm-inside-diameter subcores were collected from each box core. These cores were 48-cm-long, clear, polycarbonate tubes that were capped, top and bottom, and removed from the box cores with the overlying water from the box core retained in the subcore. Each core was acoustically logged at 1-cm intervals with a 400-kHz transducer/velocimeter described in Jackson and Richardson [22]. Measurements of sediment sound speed and attenuation were made after the cores were allowed to equilibrate to the ship's laboratory temperature. Some of these 72 cores were selected for laboratory analyses of sediment bulk density, porosity, undrained shear strength, grain size distribution, radionuclide concentration, and computed-tomography-imaged density structure. Analysis of sediment bulk density, porosity and grain size was accomplished by first sectioning the subcores at 1-cm intervals down to 2 cm sediment depth and 2-cm intervals below 2 cm depth. After sectioning, the bulk density and porosity determinations were made with the gravimetric (weight loss after drying) method that included dry grain density measurements with a pycnometer [22]. Shear strength measurements were performed on the top centimeter of the wet exposed sediment after extruding and sectioning the core following each measurement. Shear strength was measured at 1-cm intervals down to 10 cm sediment depth and 2-cm intervals down to 20 cm depth, and 5-cm intervals below 20 cm depth. Three subcores from one box core from each province were used to measure the concentration of radionuclides Be-7, Cs-137, and Pb-210 at 0.5-cm intervals down to 3 cm sediment depth and 1-cm intervals below 3 cm depth [23]. Five of the PCA subcores were chosen, based on visual evidence of biogenic structures such as burrows, for later scanning with Computed Tomography (CT) imaging in the laboratory. The subcores were "killed" with 5% formalin/seawater solution immediately after collection and resealed for acoustic logging and later use.

2) Permeability Subcores: One 5.9-cm-inside-diameter subcore was collected from each of the 24 box cores. Each subcore was 13 cm in length and was inserted whole into a SoilTest (Evanston, IL) laboratory permeameter to measure the hydraulic conductivity of the top 13-cm of the sediment from the box core.

3) X-radiograph Subcores: Two 43×33×3 (L×W×Thickness) cm "slab" subcores were collected from each of the four provinces. The subcores were brought back to the laboratory and x-rayed at 50 kV and 20 mA. A couple of x-radiograph images are presented in [23].

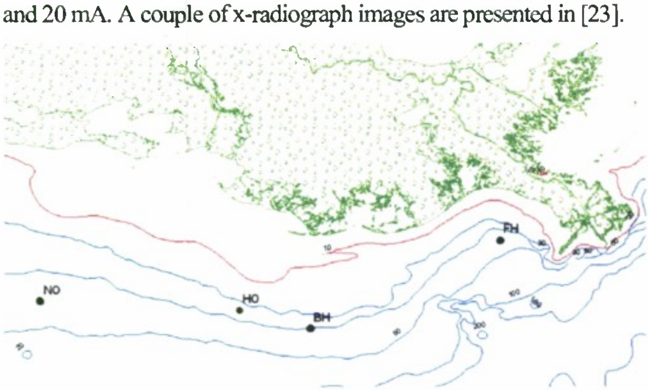

Figure 1. Location of provinces NO, HO, BH, and FH in the northern Gulf of Mexico. Depth contours are in meters.

4) Biocores: Three 8.2-cm-I.D. subcores were collected from each box core for determination of macrofauna density and diversity [24]. These subcores were 30-cm-long, clear, polycarbonate tubes that were capped for removal from the box core, but sectioned and sieved aboard ship. Each subcore was sectioned at 1-cm intervals down to 2 cm depth, 2-cm intervals from 2 to 10 cm depth, and 5-cm intervals below 10 cm depth. Each section was sieved through a 0.3-mm screen that was saved and fixed in a 5% formalin/seawater solution containing Rose Bengal vital stain.

Sediment Profile Imaging (SPI) Camera: Three deployments of the SPI camera were made at each of the four provinces. The instrument is based on an earlier design of [23],[24]. The SPI camera photographs the sediment-water interface in order to identify faunal communities and determine the depth of the redox potential discontinuity that demarcates the change from the oxidized sediment at the surface to the reduced sediment below. Some of these images are presented in [23].

Acoustic Sediment Classification Sonar: We ran five or six 1-km survey lines separated by 200 to 250 m at each province using the *R/V Pelican*'s hull-mounted acoustic fathometer. The fathometer's source is a 12-kHz signal, with a 4-kHz bandwidth and a source level of 210 dB/m re 1 μPa at 1 m. Its signal is a 4-cycle pulsed sine wave with a 0.3-ms pulse width and 500-ms repetition rate. The beamwidth is 15°. The acoustic reflection intensity was recorded and is directly proportional to sediment bulk density and is correlated with sediment grain size. These data were collected in order to ascertain the spatial heterogeneity of the sediments in each province.

III. Results

A. Sediment Sound Speed and Attenuation

Sediment sound speed is presented at the velocity (V_P) ratio, which is calculated as the speed of sound in the sediment divided by the speed of sound in the overlying water [22]. Values expressed as V_P ratio are independent of temperature. salinity, and water depth. Sediment sound attenuation is a measure of the dissipation of acoustic energy by friction (intrinsic attenuation) and by scattering from large particles embedded in the mud matrix [22].

The sediment sound speed at the normoxic province (NO) displays high variability throughout the core length (Fig. 2). Some of the variability is due to a storm layer composed of fine sand located at 2 to 4 cm sediment depth. Another source of variability in values of sediment sound speed is the coarse shell material embedded in the mud. Sediment sound attenuation at the NO province also shows much variability as a function of depth in the sediment (Fig. 3).

The sediment sound speed at the briefly hypoxic province (BH) displays high variability only in the 2 to 4 cm depth interval, indicating an increase in sound speed in a coarse (fine sand and silt) storm layer (Fig. 4). Values of sediment sound attenuation at the BH province are generally low (between 0.1 and 0.4 dB/m·kHz), but are anomalously high (> 1.0 dB/m·kHz) in the 2 to 4 cm sediment depth interval in which the storm layer is found (Fig. 5).

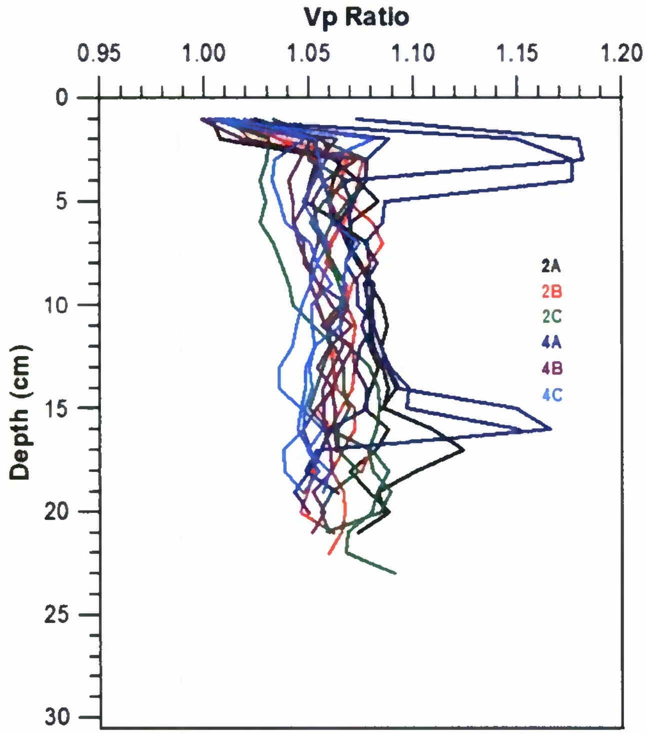

Fig.2. Sediment sound speed (V_P) ratio as a function of depth in the sediment at the normoxic (NO) province.

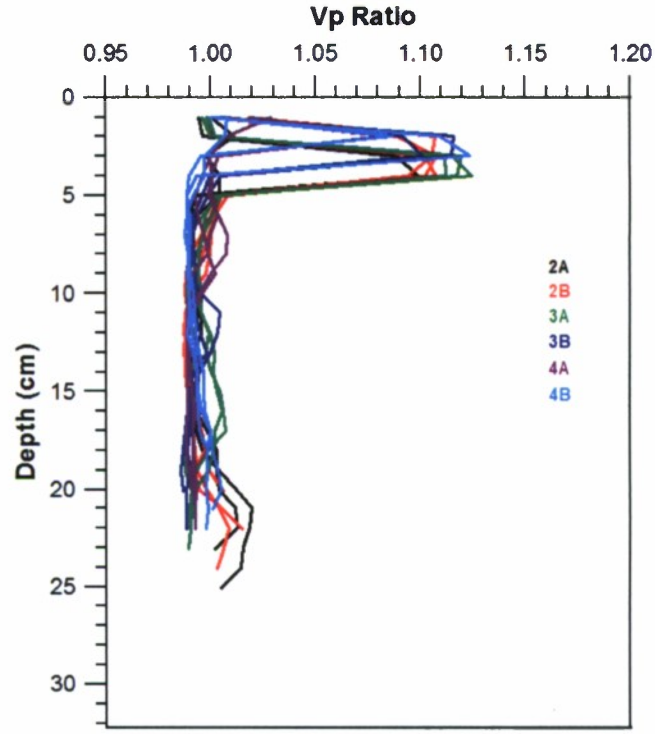

Figure 4. Sediment sound speed (V_P) ratio as a function of depth in the sediment at the briefly hypoxic (BH) province.

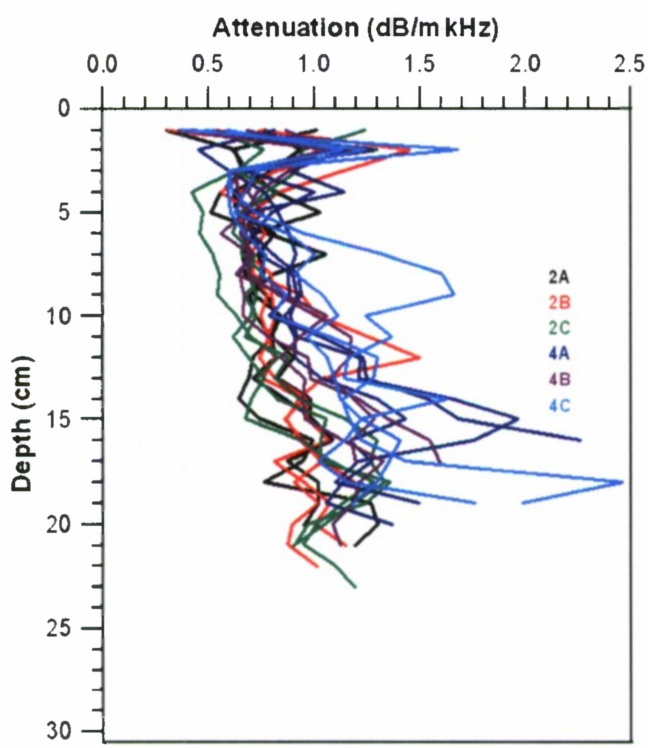

Figure 3. Sediment sound attenuation as a function of depth in the sediment at the normoxic (NO) province.

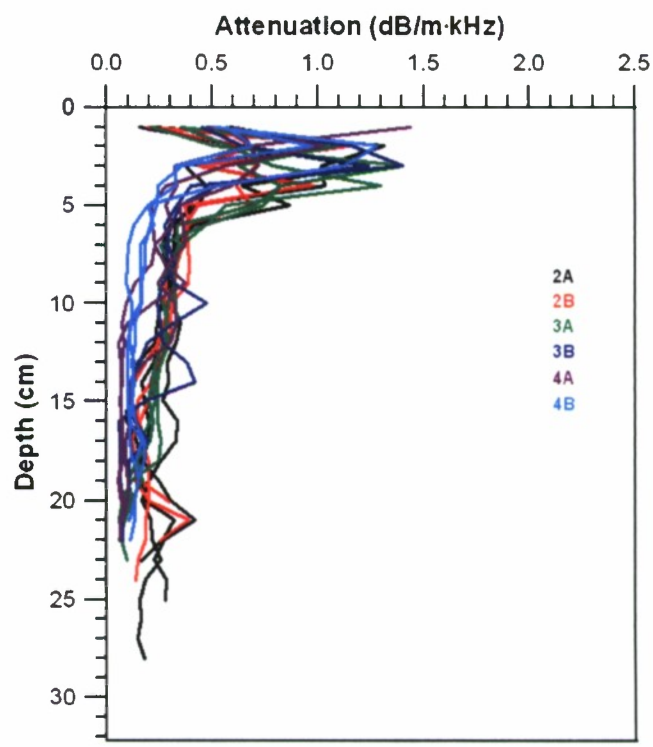

Figure 5. Sediment sound attenuation as a function of depth in the sediment at the briefly hypoxic (BH) province.

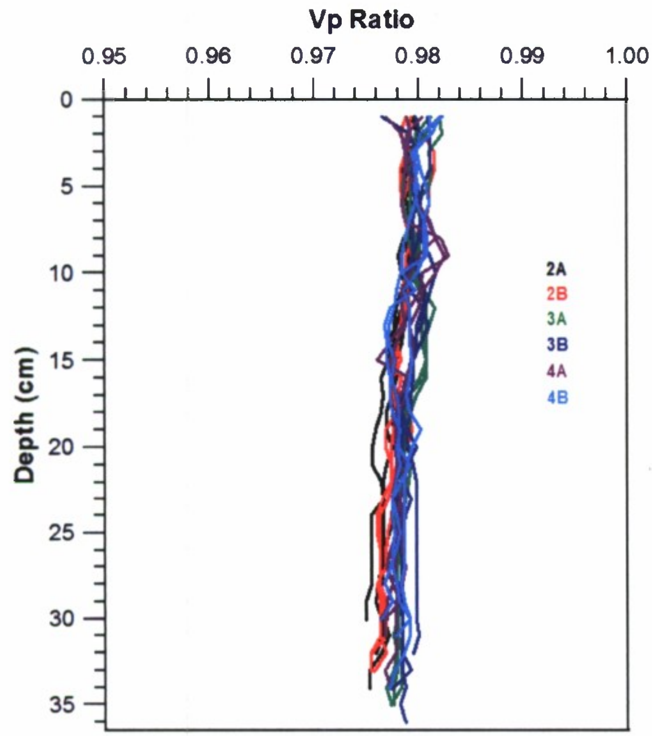

Figure 6. Sediment sound speed (V_P) ratio as a function of depth in the sediment at the frequently hypoxic (FH) province.

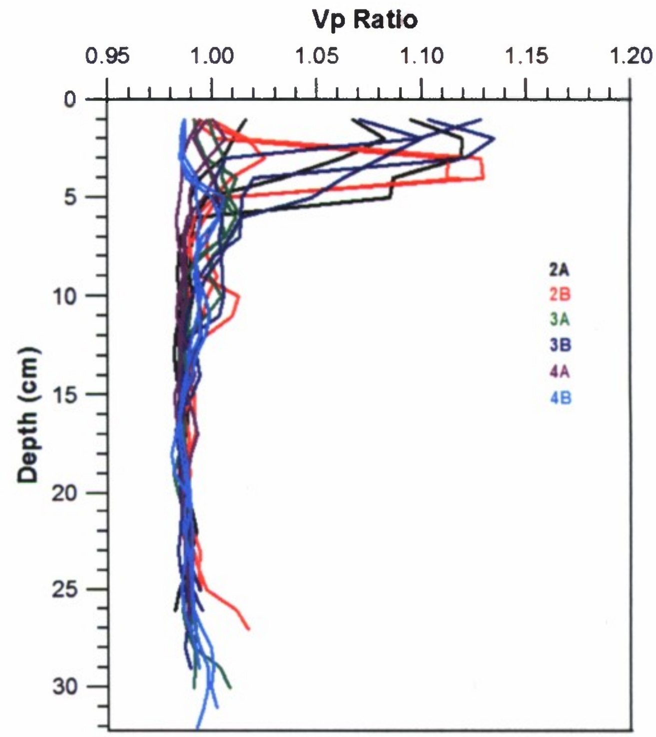

Figure 8. Sediment sound speed (V_P) ratio as a function of depth in the sediment at the hypoxic (HO) province.

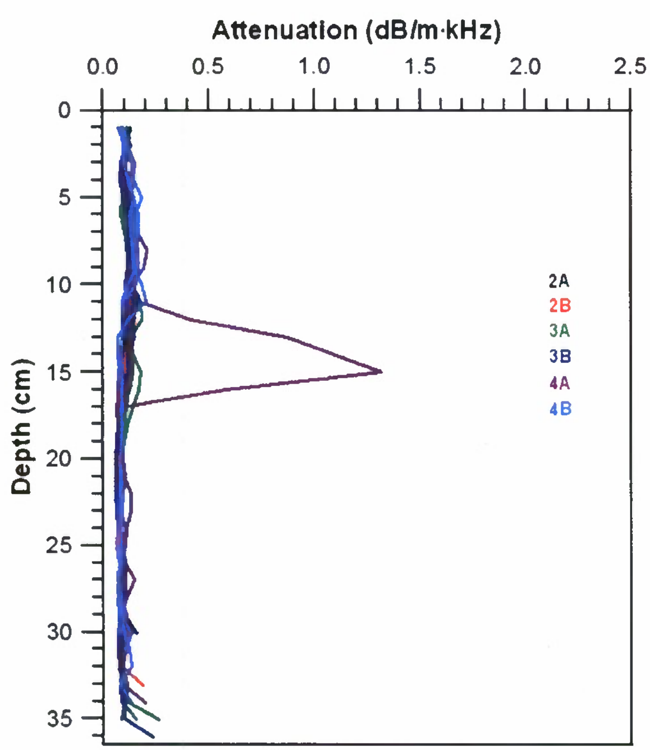

Figure 7. Sediment sound attenuation as a function of depth in the sediment at the frequently hypoxic (FH) province.

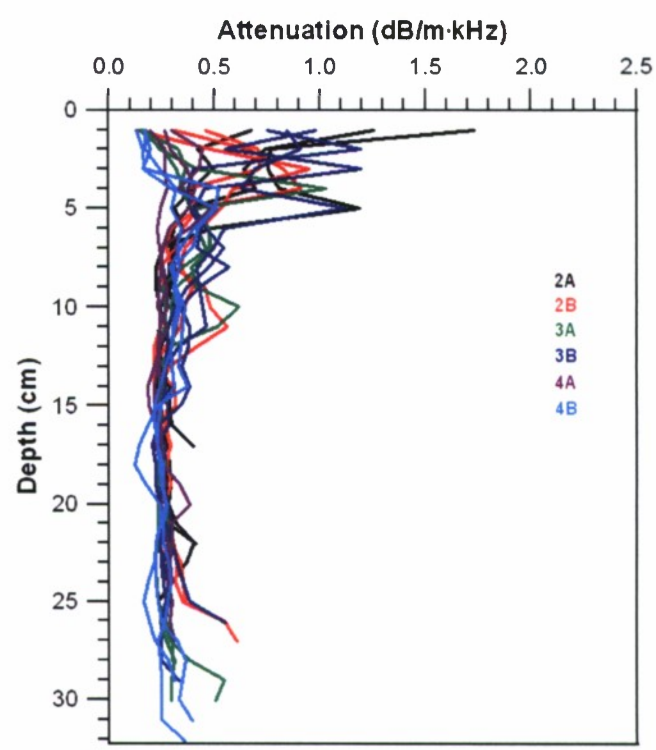

Figure 9. Sediment sound attenuation as a function of depth in the sediment at the hypoxic (HO) province.

Anomalously high sound attenuation values are often characteristic of scattering from interfaces between two sediment types. In this case, scattering may be occurring at the interface between sand or silt and the sand-silt-clay matrix above and below the fining-upward sequence that defines the storm layer.

The sediment sound speed at the frequently hypoxic province (FH) is very uniform with depth in the sediment (Fig. 6). The province closest to the mouth of the Mississippi River has a sediment sound speed that is consistently less than that of water (average V_P ratio of 0.979). The sediment sound attenuation at the FH province is consistently low as a function of depth, except for one core (4A) that has anomalously high values for attenuation at 12 to 16 cm sediment depth (Fig. 7).

The sediment sound speed at the hypoxic province (HO) is similar to that at the BH province: uniformly low, but with faster values at 1 to 6 cm sediment depth due to a coarser storm layer (Fig 8). This storm layer is also evident in the profile of sediment sound attenuation at the HO province as a 5-cm-thick zone of high (> 0.75 dB/m·kHz) attenuation values (Fig. 9).

B. Sediment Shear Strength

Undrained sediment shear strength is typical for sand-silt-clay sediments, though vertical profiles indicate slight differences among the four provinces. The frequently hypoxic (FH) and hypoxic (HO) provinces has the weakest values of sediment rigidity (0.6 and 0.8 kPa, respectively) and the least steep gradient of shear strength as a function of sediment depth (Figs 10-13).

C. Sediment Grain Size Distribution

The sediment at the normoxic province (NO) is an extremely poorly sorted sand-silt-clay with varying amounts (0-22% of dry weight) of carbonate shells and shell hash. Most of the shell material occurs below 10 cm sediment depth. The mean grain size is 4.9 phi. Phi values are the negative base-two logarithm of the grain diameter in millimeters.

The sediment at the briefly hypoxic province (BH) is an extremely poorly sorted sand-silt-clay with a mean grain size of 8.3 phi. There is a fine sand/silt layer that is upward fining between 1 and 3 cm sediment depth.

The sediment at the frequently hypoxic province (FH) is a poorly sorted silty clay with a mean grain size of 8.1 phi. Although x-radiograph images indicate a storm layer around 8 cm sediment depth, the vertical profiles show a uniformly fine mean grain size.

D. Sediment Bulk Density and Porosity

The highest values for sediment bulk density are found at the normoxic (NO) province (Figs. 14-17). The average density of 1.819 g/cm^3 was undoubtedly influenced by the high concentration of carbonate shell material embedded in the sand-silt-clay matrix. Provinces BH and HO have typical values for sand-silt-clay sediment (1.597 and 1.519 g/cm^3, respectively). The sediment at province FH is very low density silty clay with an average value of 1.289 g/cm^3. Average values for sediment porosity for provinces NO, BH, FH, and HO are 0.519, 0.654, 0.830, and 0.700, respectively.

E. Sediment Permeability

The top 13 cm of sediment at the four provinces is almost impervious. There is a high variability in the measurements, with the values of permeability varying between 4.13×10^{-15} and 8.72×10^{-15} m^2. At this point in the analysis only half of the subcores have been analyzed and we expect a wide range of values due to the presence and absence of biogenic structures in sediments from the four provinces.

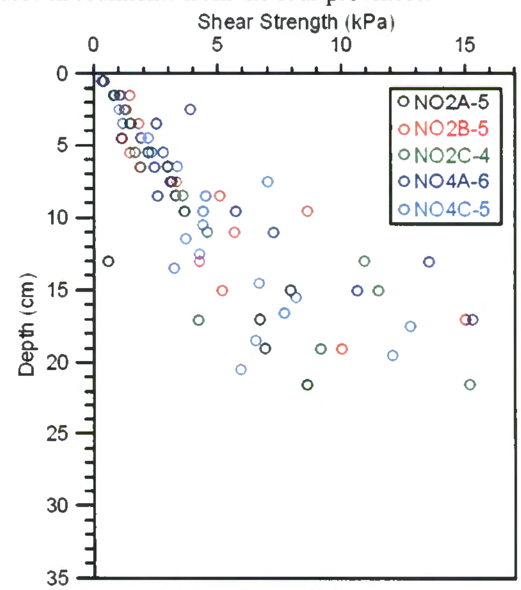

Figure 10. Vertical profile of undrained sediment shear strength at the normoxic (NO) province.

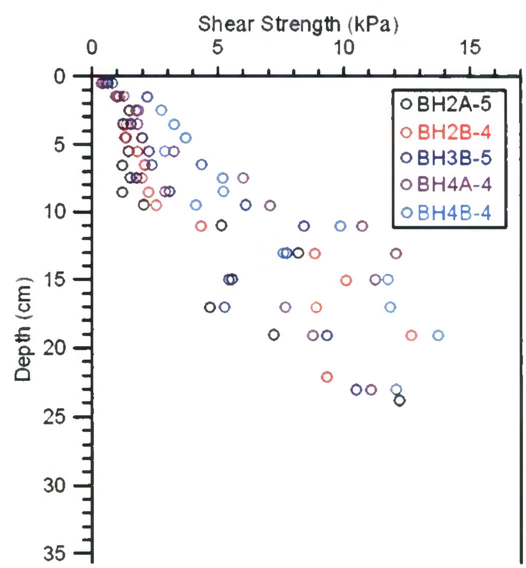

Figure 11. Vertical profile of undrained sediment shear strength at the briefly hypoxic (BH) province.

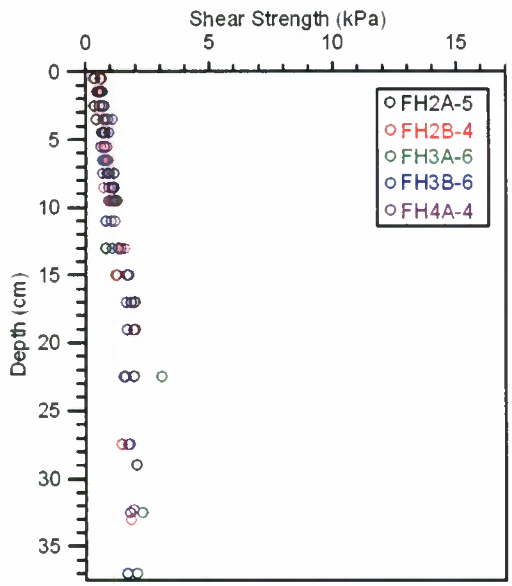

Figure 12. Vertical profile of undrained sediment shear strength at the frequently hypoxic (FH) province.

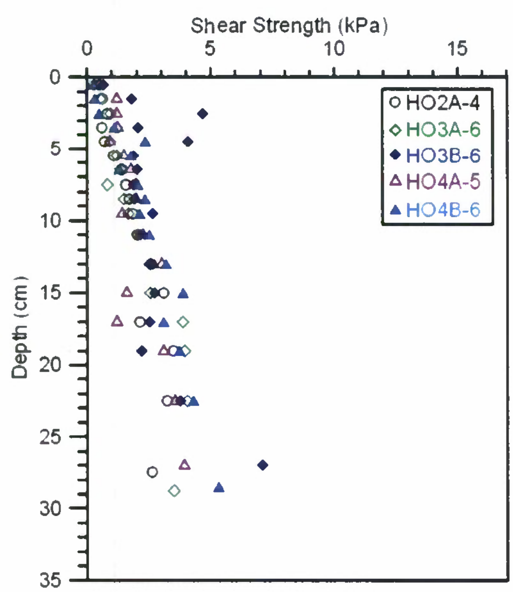

Figure 13. Vertical profile of undrained sediment shear strength at the hypoxic (HO) province.

IV. Future Work

The second cruise of 2009 is scheduled for late summer (September) aboard the *R/V Pelican*. The same four provinces will be visited and the same types and numbers of samples will be collected with the objective of documenting changes in biological and physical properties of the sites undergoing hypoxic stress. An essential part of this study will involve the characterization of the variability of the physical and acoustic properties within and among the four provinces. Due to the highly variable nature of the spatial distribution of benthic invertebrates, representative sampling of both macrofauna and sediment properties is the *sine qua non* for successful interpretation of our results.

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We would like to thank the captain and crew of the *R/V Pelican* as well as fellow scientific crew members Sarah Epps, Jason Dale, Kersey Sturdivant, and Mike Richardson for a successful cruise.

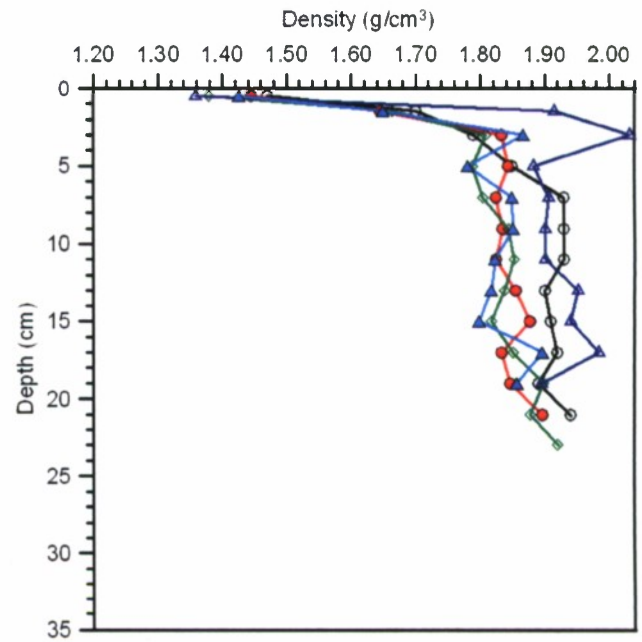

Figure 14. Sediment bulk density as a function of depth in the sediment at the normoxic (NO) province.

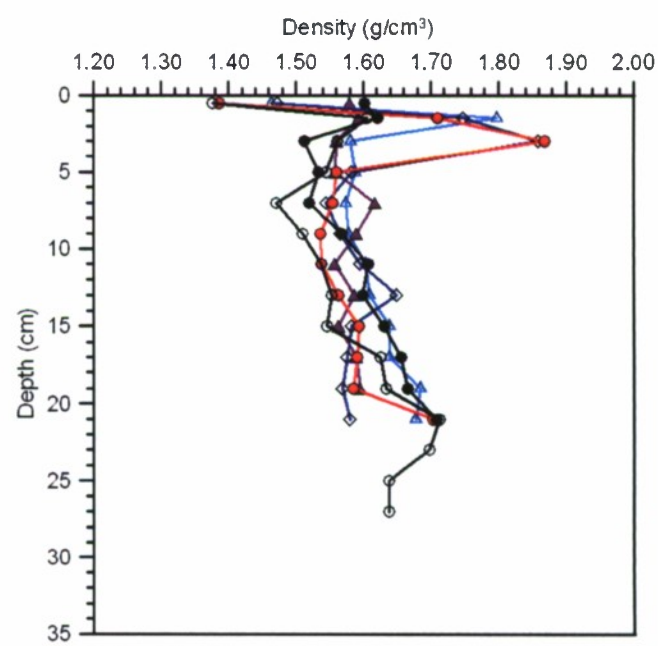

Figure 15. Sediment bulk density as a function of depth in the sediment at the briefly hypoxic (BH) province.

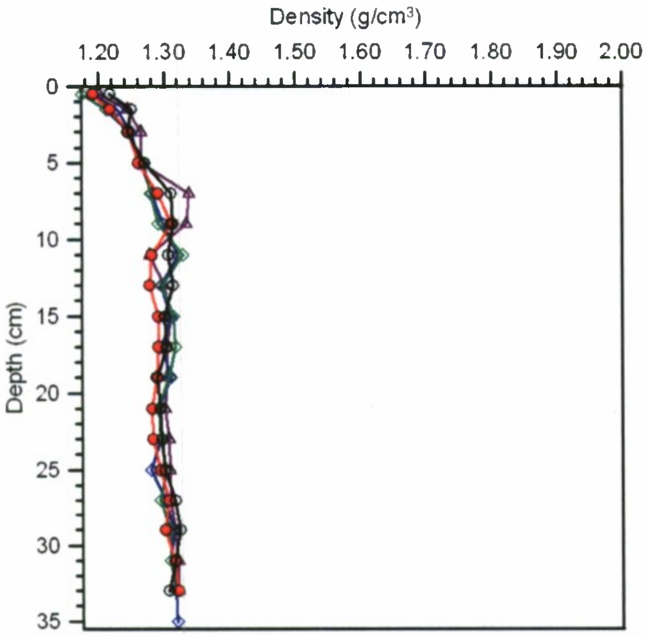

Figure 16. Sediment bulk density as a function of depth in the sediment at the frequently hypoxic (FH) province.

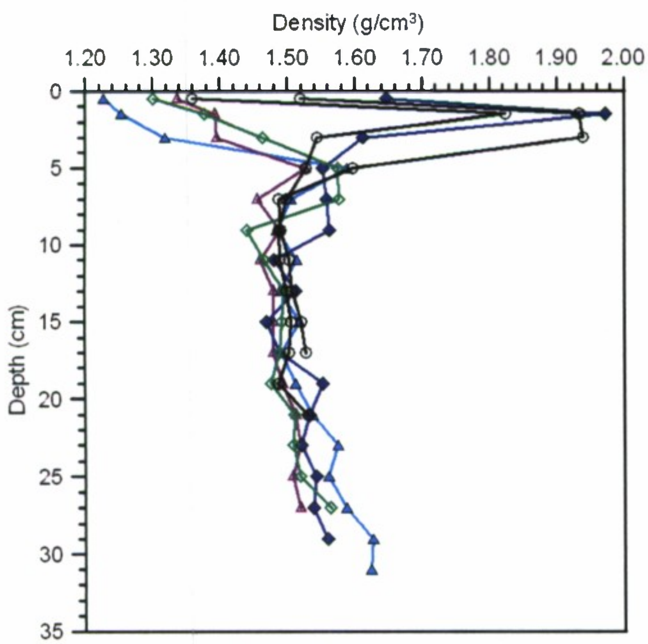

Figure 17. Sediment bulk density as a function of depth in the sediment at the hypoxic (HO) province.

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