The Use of Computed Tomography to Measure Biogenic Structures in Recently Hypoxic and Normoxic Sediments on the Louisiana Continental Shelf

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THE USE OF COMPUTED TOMOGRAPHY TO MEASURE BIOGENIC STRUCTURES IN RECENTLY HYPOXIC AND NORMOXIC SEDIMENTS ON THE LOUISIANA CONTINENTAL SHELF

by

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ABSTRACT

THE USE OF COMPUTED TOMOGRAPHY TO MEASURE BIOGENIC STRUCTURES IN RECENTLY HYPOXIC AND NORMOXIC SEDIMENTS ON THE LOUISIANA CONTINENTAL SHELF

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Over the past 60 years, seasonal hypoxia in the northern Gulf of Mexico has occurred with increased severity and over a greater area. To determine if biogenic structures in the northern Gulf of Mexico vary in response to hypoxic stress, the seafloor on the continental shelf of Louisiana was analyzed during the spring and fall of 2009 at four provinces of similar sediment type that differ in recent history of bottom water oxygen concentration. Subcores were analyzed by computed tomography (CT) to determine the number, diameter, length, volume, surface area, and depth of biogenic burrow structures in sediments where biogenic mixing rates, sedimentation rates, mixing depth, and invertebrate macrofauna abundance were known. Because benthic community composition and density determine what types of biogenic structures are present and at what rate bioturbation occurs in sediments, the quantification of mixing rates and various physical parameters of biogenic structures reveals potentially important information about the effects of hypoxia on the macrobenthic community. Results show that macrobenthic burrows were the most numerous at province NO, which had not experienced hypoxia in the past ten years. However, at the province most recently affected by hypoxia (FH), burrow abundance was the second highest out of all four provinces. The proximity of province FH to the mouth of the Mississippi River coupled
with a high sedimentation rate and high deposition of organic matter at this site could increase bioturbation activities and lead to increased burrow abundances. The CT subcore taken from the province that had experienced hypoxia one year previous to the study (HO) contained significantly longer burrows with greater median volumes, surface areas, and diameters than burrows at the other three provinces. Province HO also had high abundances of macrofaunal organisms and high rates of bioturbation. This could indicate that the macrofaunal community at province HO is in an active phase of recovery from hypoxia. In conclusion, computed tomography is a non-invasive, high resolution imaging technique that provides a means to accurately quantify the effects of hypoxia on macrobenthic bioturbation structures in marine sediments.
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CHAPTER I

INTRODUCTION

The History of Hypoxia in the Gulf of Mexico

Hypoxia, or low oxygen ($O_2$) concentration, is present in coastal bottom waters around the world (Diaz and Rosenberg, 2001) and over the past 60 years it has become more prevalent, especially in coastal areas such as the northern Gulf of Mexico, Chesapeake Bay, and areas associated with the Baltic Sea (Diaz and Rosenberg, 2008). In fact, previous studies indicate that hypoxia has become a recurring seasonal phenomenon on the Louisiana continental shelf, first appearing in the spring, intensifying in the summer, and declining in the fall (EPA, 2008). When bottom waters become hypoxic ($<2$ mg/L of $O_2$), fauna living in the water column and in upper layers of the sediment may be adversely affected (Diaz and Rosenberg, 1995). The underlying cause of hypoxia in this region is a matter of ongoing debate, but the conventional explanation states that hypoxia on the northern Gulf of Mexico shelf is a result of anthropogenic nutrient inputs (SAB, 2008). The nutrients, which are derived from fertilizers released into the Mississippi River watershed, enrich riverine inputs to the northern Gulf of Mexico with nitrogen and phosphorus (SAB, 2008). This in turn stimulates phytoplankton blooms and the production of organic matter. When the organic matter, which consists of senescent algae and zooplankton fecal pellets, falls below the seasonal pycnocline to the seafloor, it is decomposed primarily by bacteria and oxygen is depleted from the water column. This process of organic enrichment and consequent biological oxygen demand (i.e., eutrophication), in combination with water column density stratification, leads to seasonal and persistent hypoxia in bottom waters on the inner continental shelf of
Louisiana (Boesch et al., 2009). Alternative causes of and influences on hypoxia include the heterotrophic oxidation of non-riverine organic matter (Bianchi et al., 2010), meteorological processes controlling water column stratification (Dagg et al., 2007), and the loss of coastal wetlands (Bianchi et al., 2008). Today the northern Gulf of Mexico is thought to be the largest zone of coastal seasonal hypoxia in the western hemisphere (Rabalais et al., 2007).

The spatial and temporal extents of hypoxia on the continental shelf of Louisiana vary from year to year. Systematic bottom water oxygen concentration surveys of the northern Gulf of Mexico (GOM) from the Baliza delta to the Louisiana-Texas border have been conducted on an annual basis since 1985 (Rabalais et al., 2002, 1991). The total area of hypoxia has increased from approximately 8,000 km$^2$ in 1985 to an estimated 22,000 km$^2$ (Rabalais et al., 2007). Continuously recording (15-min interval) oxygen meters were deployed off Terrebonne Bay in 1990 to monitor bottom water oxygen concentrations (Rabalais et al., 1994). Findings indicate that bottom water oxygen concentrations vary within individual years and between years, but in general, concentrations gradually decline through the fall and winter, with periodic reoxygenation from wind-mixing events that break down the water column stratification and allow oxygenated surface water to replace the oxygen-deficient bottom water. Hypoxia intensifies during the spring and summer, persisting with little disruption from May through September when warm, low-salinity surface waters overlay the denser, more saline Gulf waters (Rabalais et al., 2002). An exposure gradient develops that may affect benthic communities and sediment properties differentially, according to frequency, severity, or duration of hypoxic conditions.
The Effect of Hypoxia on Benthic Invertebrate Bioturbation Activities

Prolonged hypoxic episodes in estuaries and coastal regions are becoming commonplace around the world (Diaz, 2001; Diaz and Rosenberg, 2008). Depending upon the areal extent and duration of hypoxia in a region, hypoxia can have serious impacts on benthic communities (Diaz and Rosenberg, 2001). Studies have shown that the onset of a hypoxic event can lead to declines in benthic species richness, abundance, and biomass (Diaz and Rosenberg, 2001; Lim et al., 2006; Rabalais et al., 2001). Hypoxia affects the bioturbation activities of benthic infauna, resulting in behavioral effects such as decreased movement (Tyson and Pearson, 1991), decreased burrowing depth (Diaz et al., 1992), and emergence from the sediment (Nilsson and Rosenberg, 1994).

The displacement and mixing of sediment by animals is defined as bioturbation. Evidence of bioturbation includes crawling traces, burrow structures, tubes, and the obliteration of primary sediment structures (D’Andrea and Lopez, 1997). It is important to study the bioturbation activities of benthic macrofauna for a number of reasons. When infauna move, feed, excavate sediment, and construct and irrigate burrows, they affect sediment physical properties (Meadows and Meadows, 1991), sediment redox profiles (Weissberger et al., 2009), and sediment biogeochemistry (Aller, 1982). The structures produced by the benthic fauna have various effects on the overlying water column and surrounding environment. For example, biogenic structures in surface sediment layers can affect turbulence and advection currents above the sediment-water interface (Luckenbach, 1986; Yager et al., 1993). Bioturbation also affects larval and juvenile recruitment of various biota (Woodin et al., 1998), mechanical properties of the
sediment-water interface such as hardness and surface cohesion (Bokuniewicz et al., 1975), and acoustic signal absorption and reflection (Briggs and Richardson, 1997).

Benthic fauna are influenced by hypoxia according to a model developed by Pearson and Rosenberg (Pearson and Rosenberg, 1978; hereafter called the P-R model), which defines a pattern related to equilibrium and pioneering faunal species, abundance, and biomass that occurs along a gradient of increasing organic matter in the benthic marine environment. The P-R model states that as the sediment becomes more enriched with organic matter, the sediment becomes increasingly eutrophic, and the environment shifts from a “normal” state with a redox potential discontinuity (RPD) depth deep in the sediment, to a “transitory” state with a shallower RPD, and finally to a “polluted,” anoxic state with RPD at the sediment surface. The RPD is defined as the depth in the sediment at which there is a division between oxidized and reduced chemical conditions (Lyle, 1983). “Normal” zones of organic matter enrichment are characterized by high macrofaunal diversity, large-sized macrofauna, deep-burrowing macrofauna, and low sediment porosity. However, “polluted” zones with very high organic matter enrichment are characterized by low macrofaunal diversity, small-sized macrofauna, non-burrowing macrofauna, and high sediment porosity. “Transitory” zones are characterized by properties lying somewhere along the gradient from “normal” to “polluted” (Pearson and Rosenberg, 1978).

More recent studies (Heip, 1995; Nilsson and Rosenberg, 2000) have further developed the P-R model of 1978, and many organic-matter-loaded systems stressed by hypoxia have closely fit the P-R response model (Baustian et al., 2009; Dauer et al., 1992; Diaz and Rosenberg, 2001; Harper et al., 1991; Lim et al., 2006; Nilsson and
Rosenberg, 2000; Rabalais et al., 2001; Rhoads and Germano, 1982; Rosenberg et al., 2002; Weissberger et al., 2009; Weston, 1990). This study will evaluate how closely the northern GOM fits certain aspects of the P-R model by analyzing sediment cores obtained from provinces periodically exposed to bottom waters ranging from normoxic to hypoxic. According to the P-R model, areas of rapid deposition (organic and inorganic sediment) and low bottom-water oxygen concentrations (<2 mg/L) are colonized by benthic communities characterized by low organism abundance, low biodiversity, and low biomass. Organisms, few in number and small in size, are expected to be concentrated near the sediment-water interface, remaining above the depth of the redox potential discontinuity (RPD). In contrast, well-oxygenated areas are expected to have abundant, diverse benthic communities that include larger, deeper burrowing fauna dominated by infaunal deposit-feeders, such as “head-down” conveyor-belt feeders and tubicolous polychaetes. These abundant, diverse, deep-burrowing benthic fauna help to create and maintain a deeper RPD. The effects on the sediment by the species relatively unhampered by oxygen stress, which include intensive particle mixing, should result in homogenized sediments, void spaces produced by feeding, and a rough sediment-water interface covered with feeding pits and fecal or excavation mounds. CT imagery in combination with infaunal abundance data and radionuclide data are employed to provide information on biogenic burrow structures, benthic infaunal distribution, and bioturbation activity in the sediment.

The Use of Computed Tomography to Study Bioturbation

Computed tomography (CT) is a non-destructive method of investigation first developed in 1972 to study the internal structures of the human body (Hounsfield, 1972).
Since 1972, CT has been adapted by geologists to determine the internal structure of rocks and marine sediment cores (Wellington and Vinegar, 1987). Cross-sectional image slices of an object are produced by CT when an x-ray tube rotates around the object, transmitting x-rays that are converted into photons. The photons are received by a detector and reconstructed by a back-projection algorithm. This process results in a full swath of cross-sectional images that are displayed on a computer monitor. The images are composed of pixels, which are a measure of the linear attenuation coefficient µ defined by Beer’s law: \( I = I_0 e^{-\mu x} \), where \( I_0 \) is the intensity of incident photons, \( I \) is the intensity remaining after the x-ray passes through the sample, and \( x \) is the width of the sample. The density and atomic composition of the scanned object determines how much the x-rays are attenuated (Wellington and Vinegar, 1987).

Although changes in benthic communities in relation to hypoxic stress have been documented in the Gulf of Mexico (Harper et al., 1991; Rabalais et al., 2001), the effect of hypoxia on bioturbation structures using CT has not been studied in this area. There are a handful of studies that have used CT to determine the effect of pollution and other environmental stressors on bioturbation structures of benthic communities found outside of the northern Gulf of Mexico (Mermillod-Blondin et al., 2003; Michaud et al., 2003; Perez et al., 1999; Rosenberg and Ringdahl, 2005; Weissberger et al., 2009).

A CT procedure to quantify tubes and tunnels at the community level in marine sediments was first developed by Perez et al. (1999) who chose to use CT instead of available 2-dimensional (2D) imaging techniques because of the advantages offered by CT. The main advantage of CT over 2D imaging techniques such as x-radiography or sediment profile imagery (SPI), a technique used to photograph the sediment-water
interface using a remotely deployed camera (Rhoads and Germano, 1982), is the ability to accurately depict, isolate, and quantify internal structures of various densities within different media types (Perez et al., 1999). X-radiography and SPI photography are limited because they capture essentially a 2D slice of biogenic/geologic structure, while CT can provide a three dimensional representation of an object. CT images can be rotated to view an object at any angle and can be cut along any x-, y-, or z-plane to show the interior of the object. X-radiographic images are problematic because features that are located in different planes appear to be superimposed upon one another.

Hypothesis and Objectives

Although great advances have been made in quantifying biogenic burrow structures using CT, this is a relatively new application for CT and procedures are still being refined and developed in order to provide accurate data without consuming too much time and digital storage space. The goal of the proposed study is to use CT to quantify the following parameters of burrow structures: number, depth, length, diameter, surface area, and volume. In addition to these CT measurements, collateral data from radiochemistry analyses and enumeration of infauna present in sediment cores collected concomitant with the CT-scanned cores will be presented to help interpret the effects of hypoxia on the sediments imaged with CT.

It is hypothesized that the presence, persistence (i.e., length of time), and frequency of hypoxia impact what type of benthic communities are found in a particular location and thus the rates and types of bioturbation and biogenic structures produced by benthic communities dwelling in normoxic, recently hypoxic, and frequently hypoxic conditions. The study sites are expected to follow the P-R model, which states that
benthic macrofauna communities exposed to hypoxia should be less populous, less biogenically mixed, and characterized by smaller and shallower burrow structures than benthic macrofauna communities outside the zones of hypoxia. The following four objectives were formulated to address the hypothesis:

1) Visualize and quantify various parameters (i.e., number, diameter, length, surface area, and volume) of infaunal burrows in the upper 10 cm of sediment cores taken during the spring and late summer seasons from four provinces differing in their exposure to hypoxia in order to determine if hypoxia has a measurable effect on infaunal burrows.

2) Determine if there is a significant difference among provinces and between seasons in terms of length and diameter of infaunal burrows.

3) Determine how the total volume occupied by infaunal burrows varies with depth in the sediment.

4) Compare burrow parameter results to the independently made measurements of macrofaunal abundance, biogenic mixing rate and depth, and grain size data.
CHAPTER II

METHODS

Coring and Sampling

Samples for this project were collected during two cruises on the R/V Pelican along the continental shelf of Louisiana, the first during 30 March to 6 April 2009 and the second during 5 to 11 September 2009. Results from the first cruise are presented as baseline data to establish benthic macrofauna densities and sediment properties before development of seasonal hypoxia for that year, whereas the second cruise allows us to assess the effects of the 2009 seasonal hypoxia and possible recovery from past hypoxia at the sample sites. Four different “provinces” were chosen for sampling using bottom water oxygen concentration data from the Louisiana Universities Marine Consortium (LUMCON) and archived sediment data (Naval Oceanographic Office, 2007). The four provinces are designated as a normoxic province (NO) that has not experienced hypoxia within the past nine years, a briefly hypoxic province (BH) that experienced hypoxia as recently as three years before our sampling, a hypoxic province (HO) that experienced hypoxia as recently as two years before our sampling, and a frequently hypoxic province (FH) that was hypoxic during sampling (Figure 1). Province FH also experienced hypoxia the year prior to sampling. The individual frequencies and recent histories of seasonal hypoxia at the NO, BH, FH, and HO provinces are displayed in Figure 2. The sediments of the four provinces are described as silty-clay. However, province NO contains a higher percentage of gravel-size material (>2 mm) than the other three provinces (Appendix F).
At each province a total of six 50-cm×50-cm box cores were retrieved from either two or three stations. From each box core were collected six to seven subcores, which included three 8.2-cm inside diameter (i.d.) subcores for identification and counting of invertebrate infauna (biocores) and three 5.9-cm i.d. subcores for measurement of various sediment parameters that included physical, chemical, acoustic, and burrow structure properties (PCA subcores). Five subcores were selected from the first cruise and ten subcores were selected from the second cruise as candidates for computed tomography (CT) analysis of burrow structures. Subcores that were selected for later CT analysis were “killed” with formaldehyde on board ship to arrest post-collection bioturbation activity. During the cruise, the PCA subcores were refrigerated and stored upright in Styrofoam containers. At the conclusion of each cruise, the subcores were kept cool with icepacks and transported carefully, in an upright position, to the Naval Research Laboratory at Stennis Space Center, MS for laboratory analyses.

*Figure 1.* Map of the Louisiana continental shelf showing the locations of the four provinces. Water depth contours are in meters.
Figure 2. Occurrence of bottom water oxygen conditions at the four provinces (NO, BH, HO, and FH) since year 2001, from which the frequency of hypoxia can be determined. The designations used for the shelf-wide hypoxia bottom water survey by N. Rabalais are shown under each histogram. The color key to bottom water oxygen concentrations is displayed at the bottom of the figure.

Computed Tomography Analysis

Of the 15 PCA subcores collected from box cores during the April and September 2009 cruises of the R/V Pelican, four subcores from the first cruise and four subcores from the second cruise were chosen for CT scanning at the Naval Research Laboratory.

The computed tomography scanner at the Naval Research Laboratory consists of an x-ray tube, a data acquisition system, an array processor, an image intensifier, and a control computer (Figure 3; Vannier et al., 1984). The x-ray beam at NRL has a potential energy and intensity of 10 to 225 keV and 0 to 3 mA, respectively. During operation, the CT subcore to be scanned is oriented vertically on a stationary platform. The x-ray tube and detector array are installed on a gantry around the platform. During the scanning
process, the x-ray source revolves around the object being scanned and transmits x-rays through the object. After the first “slice” is completely scanned, the platform is moved through the gantry in preprogrammed intervals (in this case, 10.25 µm intervals). The x-rays are converted into photons that a detector receives, and amplified using a 23-cm diameter image intensifier. The raw data from the data acquisition system produce a two-dimensional (2D) cross-sectional image of each core “slice,” a slice representing a full swath of material with a thickness of 10.25 µm. The 2D image slices consist of pixels that vary along a grayscale according to the linear attenuation coefficient, μ. The linear attenuation coefficient, μ, is defined by Beer’s law: \( \frac{I}{I_0} = \exp(-\mu h) \), where \( I_0 \) is the incident x-ray intensity and \( I \) is the intensity remaining after the x-ray passes through a thickness, \( h \), of the sample (Wellington and Vinegar, 1987). The linear attenuation coefficient depends on both bulk density and atomic number of the sample (Wellington and Vinegar, 1987). Pixel brightness is related to linear attenuation coefficients according to a scale of CT numbers called Hounsfield units. Darker pixels represent lower density materials, such as water or porous sediment, and lighter pixels represent higher density materials such as rock, shell, or consolidated sediments. The raw image slices are displayed on a computer monitor. When the slices are stacked sequentially, CT images can be reconstructed in three dimensions (3D). CT images are made up of 3D pixels called voxels. The top ten centimeters of each core were scanned, producing 1000 images that are 1024x1024 voxels, with a slice thickness of 102.5 µm, and \( x \) and \( y \) dimensions of 57.6 µm.
Figure 3. The industrial computed tomography system at the Naval Research Laboratory. Pictured above are the stationary x-ray source (A), the sample platform (B), and the detector (C).

After the computed tomography images were collected, the images were processed with four different software packages. First, the VoxelCalc software package was used to resample the images so that $x$, $y$, and $z$ dimensions for each voxel were 102 $\mu$m. The region of interest was defined for each image in order to remove the core liner from the images. Lastly, the images were corrected for the beam hardening effect, an image artifact resulting from the preferential absorption of the low-energy portion of the x-ray beam spectrum during the scanning process (Wellington and Vinegar, 1987).

Next, the processed CT images were imported into Avizo Standard, a 3D analysis software designed to handle computed tomography data sets. The purpose of this step was to separate water-filled burrows produced by benthic organisms from the rest of the material in each core. The rationale for this step is based on the method developed by
Perez et al. (1999). Histograms of the frequency distribution of pixels by CT number for each 1-cm slice, from the top of the core (0 cm sediment depth) to 10 cm sediment depth were produced (Figure 4). These frequency distributions were used to determine the voxel values separating the cores into the following components: water, water-filled burrows, and sediment. Segmentation is a crucial step for determining how burrows are defined in relation to the rest of the material in a sediment core such as water, sediment, rock, or shell. Indicator kriging is the type of segmentation chosen for this project because it uses two different linear attenuation coefficient “threshold” values, representing a lower, minimum threshold value, $T_1$, and an upper, maximum threshold value, $T_2$. 
Figure 4. Segmentation of CT images based on attenuation values. The attenuation histogram and slice images are snapshots taken using Avizo software. A) Unsegmented CT image of slice at 3 to 4 cm depth interval from province NO CT subcore. B) Histogram of segmentation results. The x-axis is attenuation value, and the y-axis is the number of voxels. Materials in CT images were identified as either water, biogenic burrows, or sediment based on the attenuation values. C) Segmented CT image of slice at 3 to 4 cm depth interval from province NO CT subcore.

$T_1$ is the value separating pure water from the more dense water-filled burrows. $T_1$ was calculated separately for each core by averaging the mean CT number for water in the top 20 slices of the core, which contained no sediment. $T_2$ was chosen because it lies between the maximum attenuation value corresponding to water-filled burrows and the minimum attenuation value corresponding to sediment. $T_2$ was determined by calculating the average maximum attenuation value of water for each core and the average minimum attenuation value of sediment without rocks or shell fragments. The value chosen for $T_2$ corresponded to that of the average minimum sediment value, unless this produced
segmented images with too much noise. In this case, the value was adjusted to be the mean of the average minimum sediment and the average maximum water. In order to verify the validity of the $T_1$ and $T_2$ assignments, the $T_1$ and $T_2$ values were checked in VoxelCalc by placing a cursor displaying attenuation values over burrows. All values were found to be accurate.

The CT images were then segmented using the Linux-based software package for automated analysis of pore structure in 3D microtomography images called three-dimensional microtomography image analysis (3DMA). Three-dimensional microtomography image analysis is a package designed to provide statistical analyses of the geometrical distribution of phases in 3D computed microtomography images. A total of 1000 images, representing 0 to 10 cm in depth, from each of the eight CT subcores were segmented using indicator kriging. A total of 1000 black-and-white TIFF (Tagged Image File Format) images of each core were produced as a result.

Finally, the water-filled infaunal burrows were quantified and visualized in 3D using ImagePro Plus. First, the segmented images produced in 3DMA were imported into ImagePro Plus as JPEG (Joint Photographic Experts Group) images. Next, the images were calibrated so that measurements would correspond to the actual dimensions of the core (in millimeters). Noise was removed, and particles smaller than 0.05 mm on a side were removed because animals larger than 0.05 mm in diameter were considered significant (K. Briggs, personal correspondence). The “3D Constructor” was used to create a 3D representation of the entire core (Figure 5; Appendix C). Next, the length of each 3D burrow was measured by manually adding points along the length of the burrow and then connecting the points using a polyline. The length of the polyline in millimeters
was then automatically calculated by ImagePro Plus. The depth of each burrow was also calculated by manually adding a point at the upper-most point of the burrow and the lower-most point of the burrow and recording these two z-values in an Excel spreadsheet. Again, ImagePro Plus automatically calculated the depth in millimeters. The following parameters were automatically calculated by ImagePro Plus and then recorded into an Excel spreadsheet: number of burrows, burrow diameter, burrow surface area, and burrow volume. Image Pro Plus was also utilized to capture 2D images of each CT subcore and movies displaying the burrows within each of the subcores as they rotate 360-degrees (Appendix G).
Figure 5. Three-dimensional representation of biogenic burrows in a CT subcore produced in ImagePro Plus. Shown is the April CT subcore from province NO. The sediment subcore is shown in an upright position, with the x-axis representing the width of the subcore and the z-axis representing the length of the subcore. Individual burrows are distinguished by color. The scale is in millimeters.

Statistical Analysis

Statistical analysis was performed on burrow structure parameter data using SPSS version 16.0. For all data sets, a Shapiro-Wilk test was performed in order to test the distribution of each parameter for normality. When normality was not observed, square-root, log, and arcsine transformations were performed on the burrow parameters. Because
the raw data and the transformed data were not normally distributed and had unequal sample sizes, non-parametric analyses were performed on CT-derived burrow data sets.

Statistical analyses of differences in burrow diameter and burrow length among the four provinces and between the April and September cruises were made by Kruskal-Wallis tests. Mann-Whitney tests were then performed to determine differences among individual provinces. Statistics were not performed on radionuclide or organic matter data since these data were used to qualitatively describe the provinces.
CHAPTER III

RESULTS

Biogenic Structures Analyzed by CT

The burrow parameters, number of burrows, burrow length, burrow diameter, total burrow surface area, and total burrow volume, were not normally distributed based on the Shapiro-Wilk test for normality. Also, the number of burrows varied between subcores so, when subcores were compared to one another, equal sample sizes could not be assumed. Therefore, nonparametric statistics were used to analyze the CT data. In general, the data tended to be skewed to the right, signifying that the majority of the burrows were smaller in diameter, volume, etc., with a minority of the burrows having larger, outlier values. Refer to frequency histograms in the appendix to see how the data are skewed (Appendix A).

Total Number of Burrows

The total number of burrows per subcore was assessed. The September subcore from province NO (9NO) contained the highest number of burrows, precisely 165 burrows, while the April subcores from province HO (HO) contained the lowest number of burrows, 58 burrows. The total number of burrows in the April CT subcores ranged from 58 burrows (HO) to 111 burrows (NO), while the total number of burrows in the September CT subcores ranged from 148 burrows (9BH) to 165 burrows (9NO).

Results indicated that the September subcores contained over 30% more burrows than the April subcores. Specifically, subcores taken from province NO indicated an increase in total number of burrows from 111 burrows in April to 165 burrows in September. Numbers of burrows in subcores from province BH increased from 101 to
Burrows in subcores from province HO nearly tripled, increasing from 58 to 160. Lastly, numbers of burrows in the subcores taken from province FH increased from 105 to 161 (Figure 6).

Figure 6. Total number of burrows in each CT subcore. Blue bars indicate April subcores and red bars indicate September subcores. The provinces are designated as NO (normoxic since 2001), BH (hypoxic in 2006 and 2007), HO (hypoxic in 2006, 2007, and 2008), and FH (hypoxic in 2008 and 2009).

Length of Burrows

The results are presented in the following order: description of the data frequency distribution, description of how burrow length changes with depth in each subcore, comparison of the different provinces from which subcores were taken, and finally a comparison of April to September subcores. This presentation order is utilized to describe all other burrow parameters in subsequent sections as well.

Frequency histograms of April and September burrow lengths show that the burrow length data are all skewed to the right, with the majority of the burrow lengths
ranging from 0.4 mm to 10 mm (Appendices A, B). The highest relative frequency, or mode, of burrow lengths lies between 1 and 5 mm for all subcores.

Burrow lengths were averaged over 1 cm depth intervals from the top of the subcore to a depth of 10 cm in order to show how burrow length varied with depth. April burrow lengths appear to be randomly distributed with respect to depth. Burrows in the top 2 cm are all under 6 mm in length, but looking downcore, there is no apparent trend in burrow length. Intervals containing the longest burrows on average are 20 to 30 mm, 30 to 40 mm, and 80 to 90 mm (Figure 7). September lengths also appear to be randomly distributed with respect to depth. Burrows are longer in the top 2 cm than those in the April subcores, and they range from 2 to 10 mm in length. The longest burrows are contained in depth intervals 4 to 5 cm and 7 to 8 cm (Figure 8).
Figure 7. Average burrow length as a function of depth in the sediment for April CT subcores. The provinces are designated as NO (normoxic since 2001), BH (hypoxic in 2006 and 2007), HO (hypoxic in 2006, 2007, and 2008), and FH (hypoxic in 2008 and 2009).
Figure 8. Average burrow length as a function of depth in the sediment for September CT subcores. The provinces are designated as NO (normoxic since 2001), BH (hypoxic in 2006 and 2007), HO (hypoxic in 2006, 2007, and 2008), and FH (hypoxic in 2008 and 2009).

Because the burrow length data are not distributed normally, these data are compared using the median and range. The 25th and 75th percentile values for each subcore also were calculated to determine the range for the majority of the data (Figure 9). Arranged from longest median burrow length to shortest median burrow length, the CT subcores are listed as follows: 9HO (6.77 mm) > 9BH (5.76 mm) > HO (4.64 mm) > FH (4.15 mm) > BH (3.76 mm) > NO (3.06 mm) > 9FH (2.90 mm) > 9NO (2.51 mm).

Of the April subcores, HO had the longest median burrow length and NO had the shortest median burrow length. Province 9HO had the longest median burrow length and province 9NO had the shortest median burrow length. The April subcore with the narrowest range of burrow lengths was FH, and the April subcore with the widest range of burrow lengths...
was BH (Figure 9; Table 1). The September subcore with the narrowest range of burrow lengths was 9HO, and the September subcore with the widest range of burrow lengths was 9BH (Figure 9; Table 1).

Table 1

*Burrow Parameter Statistics for April and September CT Subcores.*

<table>
<thead>
<tr>
<th>Subcore</th>
<th>Statistics</th>
<th>Length (mm)</th>
<th>Diameter (mm)</th>
<th>Volume (mm³)</th>
<th>Surface Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO</td>
<td>Range of data</td>
<td>0.41 - 43.57</td>
<td>0.47 - 5.34</td>
<td>0.06 - 79.75</td>
<td>0.84 - 280.02</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>3.06</td>
<td>1.38</td>
<td>1.53</td>
<td>10.43</td>
</tr>
<tr>
<td></td>
<td>25&lt;sup&gt;th&lt;/sup&gt; percentile</td>
<td>2.15</td>
<td>1.09</td>
<td>0.84</td>
<td>6.00</td>
</tr>
<tr>
<td></td>
<td>75&lt;sup&gt;th&lt;/sup&gt; percentile</td>
<td>5.38</td>
<td>1.60</td>
<td>3.00</td>
<td>18.25</td>
</tr>
<tr>
<td>BH</td>
<td>Range of data</td>
<td>0.68 - 59.43</td>
<td>0.47 - 5.70</td>
<td>0.05 - 97.00</td>
<td>0.82 - 516.24</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>3.76</td>
<td>1.46</td>
<td>1.90</td>
<td>12.36</td>
</tr>
<tr>
<td></td>
<td>25&lt;sup&gt;th&lt;/sup&gt; percentile</td>
<td>2.21</td>
<td>1.03</td>
<td>0.67</td>
<td>5.70</td>
</tr>
<tr>
<td></td>
<td>75&lt;sup&gt;th&lt;/sup&gt; percentile</td>
<td>7.61</td>
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<td>5.77</td>
<td>34.83</td>
</tr>
<tr>
<td>HO</td>
<td>Range of data</td>
<td>0.43 - 53.98</td>
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<td>0.05 - 18.50</td>
<td>0.81 - 125.09</td>
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<td>Median</td>
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<td>1.56</td>
<td>2.84</td>
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<tr>
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<td>1.15</td>
<td>1.48</td>
<td>11.20</td>
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<td>7.46</td>
<td>2.12</td>
<td>6.15</td>
<td>31.98</td>
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<tr>
<td>FH</td>
<td>Range of data</td>
<td>0.72 - 43.17</td>
<td>0.47 - 7.93</td>
<td>0.05 - 260.78</td>
<td>0.82 - 471.03</td>
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<tr>
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<td>1.25</td>
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<td>0.05 - 151.83</td>
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<td>3.39</td>
</tr>
<tr>
<td></td>
<td>75&lt;sup&gt;th&lt;/sup&gt; percentile</td>
<td>4.28</td>
<td>1.55</td>
<td>2.23</td>
<td>14.82</td>
</tr>
<tr>
<td>9BH</td>
<td>Range of data</td>
<td>1.68 - 123.0</td>
<td>0.90 - 4.83</td>
<td>0.38 - 67.95</td>
<td>3.70 - 348.31</td>
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<td>1.64</td>
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<td>1.33</td>
<td>1.43</td>
<td>9.45</td>
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<tr>
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<td>10.11</td>
<td>2.05</td>
<td>5.58</td>
<td>31.84</td>
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</tbody>
</table>
Table 1 (continued).

<table>
<thead>
<tr>
<th>Subcore</th>
<th>Statistics</th>
<th>Length (mm)</th>
<th>Diameter (mm)</th>
<th>Volume (mm$^3$)</th>
<th>Surface Area (mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9HO</td>
<td>Range of data</td>
<td>0.71 – 61.40</td>
<td>0.47 – 6.66</td>
<td>0.05 – 154.77</td>
<td>0.81-526.26</td>
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<td>6.77</td>
<td>1.66</td>
<td>3.42</td>
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<tr>
<td>25th percentile</td>
<td></td>
<td>3.84</td>
<td>1.31</td>
<td>1.41</td>
<td>10.57</td>
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<td>11.61</td>
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<td>8.22</td>
<td>45.71</td>
</tr>
<tr>
<td>9FH</td>
<td>Range of data</td>
<td>0.45 – 67.98</td>
<td>0.47 – 3.22</td>
<td>0.05 – 62.26</td>
<td>0.81-297.69</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td>2.90</td>
<td>1.04</td>
<td>0.98</td>
<td>7.87</td>
</tr>
<tr>
<td>25th percentile</td>
<td></td>
<td>1.78</td>
<td>0.84</td>
<td>0.48</td>
<td>4.24</td>
</tr>
<tr>
<td>75th percentile</td>
<td></td>
<td>4.45</td>
<td>1.39</td>
<td>1.94</td>
<td>13.43</td>
</tr>
</tbody>
</table>

Statistical analysis revealed that there were significant differences among the four different provinces when comparing median burrow lengths. The Kruskal-Wallis test comparing April burrow lengths between the four provinces gave a $p$-value of 0.003, indicating that there is a difference in median burrow lengths at the $\alpha = 0.01$ level of significance. Mann-Whitney tests comparing median burrow lengths from April between the four provinces revealed significant differences between the following subcores: HO and BH, HO and NO, and FH and NO. There were no other significant differences found. The Kruskal-Wallis test comparing September burrow lengths between the four provinces gave a $p$-value of 0.001, indicating that there is a difference in median burrow lengths at the $\alpha = 0.001$ level of significance. Mann-Whitney tests comparing median burrow lengths from September between the four provinces revealed significant differences among the following subcores: 9BH and 9NO, 9BH and 9FH, 9HO and 9NO, and 9HO and 9FH. Subcores from 9BH and 9HO were not significantly different, and 9NO and 9FH were not significantly different, in terms of burrow length.
Seasonal variation between April and September at each province was also considered. Mann-Whitney tests were performed to test for differences in burrow lengths between April and September subcores from each province. Results from these tests include the following: NO had significantly longer burrow lengths than 9NO, 9BH had significantly longer burrow lengths than BH, 9HO had significantly longer burrow lengths than HO, and FH had significantly longer burrow lengths than 9FH.
Figure 9. Box-and-whisker plots of April and September burrow lengths. The plot shows the minimum, maximum, median, lower quartile, upper quartile, and outliers for each subcore. The long horizontal lines above and below each box indicate the extreme values (minimum and maximum), the box is defined by the lower and upper quartiles, and the line in the center of the box is the median. Outlier values are indicated by cross-hatches. The subcore designation indicates whether the subcore was taken in April (no numerical prefix) or in September (numerical prefix “9”) and from which province the subcore was collected. The provinces are designated as NO (normoxic since 2001), BH (hypoxic in 2006 and 2007), HO (hypoxic in 2006, 2007, and 2008), and FH (hypoxic in 2008 and 2009).
Diameter of Burrows

Frequency histograms of April and September burrow diameters show that the burrow diameter data are all skewed to the right, with the majority of the burrow diameters ranging from 0.01 mm to 5.0 mm (Appendices A, B). The highest relative frequency of burrow lengths lies between 0.5 and 3.0 mm for all subcores.

Burrow diameters were averaged over 1 cm depth intervals from the top of the core to a depth of 10 cm for each subcore in order to show how burrow diameter varied with depth. April burrow diameters appear to be randomly distributed with respect to depth (Figure 10). Burrows in the top 3 cm of the April subcores have average diameters under 2.0 mm except subcore BH, which has a notably high average diameter of 5.1 mm in the 0 to 1 cm interval. Looking downcore, there is no apparent trend that all of the subcores follow in terms of increasing or decreasing burrow diameter. The average burrow diameters in subcore NO tend to vary between 1.0 and 1.5 mm, with the highest average diameter occurring in the 5 to 6 cm interval. The average burrow diameters in core BH vary between 1.0 and 2.5 mm, with the widest average diameters occurring in the 0 to 1 cm interval. The average burrow diameters in subcore HO vary between 1.0 and 2.0 mm. Note that there were no burrows detected in the 6 to 7 cm or 9 to 10 cm intervals. The burrow diameters in subcore FH vary between 1.0 to 2.0 mm in average size from the top of the subcore to 6 cm depth. Beyond this depth, the average burrow diameter increases to 3.2 mm in the 6 to 7 cm interval and decreases to 2.3 mm in the 9 to 10 cm interval.

Burrow diameters measured from subcores collected in September also appear to be randomly distributed with respect to depth (Figure 11). However, all of the average
burrow diameters in the September subcores are less than 2.5 mm. The average burrow diameters in subcore 9NO vary from 1.0 to 2.0 mm, with the largest average burrow diameters (1.6 mm) occurring in the 8 to 9 cm and 9 to 10 cm intervals. The average burrow diameters in subcore 9BH vary from 1.0 to 2.4 mm, with the largest average burrow diameter occurring in the 4 to 5 cm interval. The average burrow diameters in subcore 9HO vary from 1.0 to 2.5 mm, with the largest average diameter occurring in the 6 to 7 cm interval, and the smallest average diameter occurring in the 9 to 10 cm interval. The average burrow diameters in subcore 9FH vary from 0.8 to 1.4 mm, with the smallest average diameter occurring in the 9 to 10 cm interval.

Figure 10. Average burrow diameter as a function of depth in the sediment for April CT subcores. The provinces are designated as NO (normoxic since 2001), BH (hypoxic in 2006 and 2007), HO (hypoxic in 2006, 2007, and 2008), and FH (hypoxic in 2008 and 2009).
Figure 11. Average burrow diameter as a function of depth in the sediment for September CT subcores. The provinces are designated as NO (normoxic since 2001), BH (hypoxic in 2006 and 2007), HO (hypoxic in 2006, 2007, and 2008), and FH (hypoxic in 2008 and 2009).

Because the burrow diameter data are not distributed normally, these data are compared using the median and range. The 25th and 75th percentiles for each subcore were also calculated in order to determine the range for the majority of the data (Figure 12). Arranged from largest to smallest median burrow diameter, the CT subcores are as follows: 9HO (1.66 mm) > 9BH (1.64 mm) > FH (1.57 mm) > HO (1.56 mm) > BH (1.46 mm) > NO (1.38 mm) > 9NO (1.15 mm) > 9FH (1.04 mm). Of the April subcores, FH had the largest median burrow diameter and NO had the smallest median burrow diameter. Of the September subcores, 9HO had the largest median burrow diameter and 9FH had the smallest median burrow diameter. The April subcore with the narrowest range of burrow diameters was HO, and the April subcore with the widest range of
burrow diameters was FH (Figure 12; Table 1). The September subcore with the narrowest range of burrow diameters was 9FH, and the September subcore with the widest range of burrow diameters was 9HO (Figure 12; Table 1).

Statistical analysis revealed that there were significant differences among the four different provinces when comparing median burrow diameters. The Kruskal-Wallis test comparing April burrow diameters among all four provinces gave a p-value of 0.001, indicating that there is a difference in median burrow diameters at the $\alpha = 0.001$ level of significance. Mann-Whitney tests comparing median burrow diameters measured in April among the four provinces revealed significant differences between the following subcores: HO and NO, FH and NO, and FH and BH. HO had significantly larger diameter burrows than NO. FH had significantly larger diameter burrows than NO and BH. There were no other significant differences found. The Kruskal-Wallis test comparing September burrow diameters among the four provinces gave a p-value of 0.001 indicating that there is a difference in median burrow diameters at the $\alpha = 0.001$ level of significance. Mann-Whitney tests comparing median burrow diameters from September among the four provinces revealed significant differences between the following subcores: 9BH and 9NO, 9BH and 9FH, 9HO and 9NO, and 9HO and 9FH. Subcore 9BH had significantly larger diameter burrows than 9NO and 9FH. Subcore 9HO had significantly larger diameter burrows than subcores 9NO and 9FH. Subcores 9BH and 9HO were not significantly different from one another, and neither were subcores 9NO and 9FH.

Seasonal variation from April to September at each province was also considered. Mann-Whitney tests were performed to test for differences in burrow diameters between
April and September subcores from each province. Results from these tests include the following: NO, BH, and FH had significantly larger burrow diameters than 9NO, 9BH, and 9FH; HO and 9HO were not significantly different in burrow diameter; and FH had significantly wider burrow diameters than 9FH.

Figure 12. Box-and-whisker plots of April and September burrow diameters. The provinces are designated as NO (normoxic since 2001), BH (hypoxic in 2006 and 2007), HO (hypoxic in 2006, 2007, and 2008), and FH (hypoxic in 2008 and 2009).
Total Burrow Volume

Frequency histograms of April and September burrow volumes show that the burrow volume data are all skewed to the right, with the majority of the burrow volumes ranging from 0.5 mm\(^3\) to 5.0 mm\(^3\). The highest relative frequency of burrow lengths lies between 0.5 mm\(^3\) to 3.0 mm\(^3\) for all subcores (Appendices A, B).

Burrow volumes were averaged over 1 cm depth intervals from the top of the subcore to a depth of 10 cm for each subcore in order to show how burrow volume varied with depth. April burrow volumes do not appear to follow a clear trend with respect to depth (Figure 13). Burrows in the top 5 cm of the April subcores have average volumes under 15 mm\(^3\). Looking downcore, the average volume of burrows in subcore NO peaks at about 16 mm\(^3\) in the 5 to 6 cm depth interval, and then stays below 5 mm\(^3\) for the rest of the subcore. Average burrow volume in subcore FH peaks at about 49 mm\(^3\) in the 6 to 7 cm depth interval and then gradually decreases to an average burrow volume of about 9 mm\(^3\) at the 9 to 10 cm depth interval. The average burrow volumes in subcore BH remain below about 12 mm\(^3\) throughout the length of the subcore and then suddenly peak at the 9 to 10 cm depth interval with an average burrow volume of about 24 mm\(^3\). The average burrow volume in subcore HO remains below about 6 mm\(^3\) throughout the length of the subcore. There were no burrows in the HO subcore in the 6 to 7 cm and 9 to 10 cm depth intervals.

Average burrow volumes from September subcores vary over a narrower range (about 0.5 mm\(^3\) to 21 mm\(^3\)) than the burrow volumes from April subcores (about 0.5 mm\(^3\) to 49 mm\(^3\)) (Figures 13, 14). Average burrow volumes for subcore 9NO increase from about 1 mm\(^3\) in the 0 to 1 cm depth interval to about 11 mm\(^3\) in the 3 to 4 cm depth
interval. The average burrow volumes remain less than about 7 mm$^3$ below this depth interval in the subcore. Average burrow volumes in subcore 9BH vary from about 12 mm$^3$ to about 0.5 mm$^3$ and peak towards the bottom of the subcore (7 to 8 cm depth interval) at about 13 mm$^3$. Burrow volumes in subcore 9HO peak in the 6 to 7 cm depth interval at about 21 mm$^3$, and the burrow volumes vary from 3 mm$^3$ to 12 mm$^3$ in the remainder of the subcore. Average burrow volumes in subcore 9FH are relatively low, peaking at 7 mm$^3$ in the 7 to 8 cm depth interval.

![Graph of average burrow volume as a function of depth in the sediment for April CT subcores. The provinces are designated as NO (normoxic since 2001), BH (hypoxic in 2006 and 2007), HO (hypoxic in 2006, 2007, and 2008), and FH (hypoxic in 2008 and 2009).](image)

*Figure 13. Average burrow volume as a function of depth in the sediment for April CT subcores. The provinces are designated as NO (normoxic since 2001), BH (hypoxic in 2006 and 2007), HO (hypoxic in 2006, 2007, and 2008), and FH (hypoxic in 2008 and 2009).*
Figure 14. Average burrow volume as a function of depth in the sediment for September CT subcores. The provinces are designated as NO (normoxic since 2001), BH (hypoxic in 2006 and 2007), HO (hypoxic in 2006, 2007, and 2008), and FH (hypoxic in 2008 and 2009).

Median, range, 25th and 75th percentiles for each subcore were calculated to statistically parameterize the burrow volume data (Figure 15). Arranged from largest median burrow volume to smallest median burrow volume, the spectrum of burrow volumes in the CT subcores are as follows: 9HO (3.42 mm³) > HO (2.84 mm³) > 9BH (2.50 mm³) > FH (2.25 mm³) > BH (1.90 mm³) > NO (1.53 mm³) > 9FH (0.98 mm³) > 9NO (0.86 mm³). Of the April subcores, HO had the greatest median burrow volume and NO had the least median burrow volume. Of the September subcores, 9HO had the greatest median burrow volume and 9NO had the least median burrow volume. The April subcore with the narrowest range of burrow volumes was HO, and the April subcore with the widest range of burrow volumes was FH (Figure 15; Table 1). The September
subcore with the narrowest range of burrow volumes was 9FH, and the September subcore with the widest range of burrow volumes was 9HO (Figure 15; Table 1).

![Box-and-whisker plots of April and September burrow volumes. The provinces are designated as NO (normoxic since 2001), BH (hypoxic in 2006 and 2007), HO (hypoxic in 2006, 2007, and 2008), and FH (hypoxic in 2008 and 2009).](image)

In order to compare this study to previous studies, total volume of all burrows within 2 cm depth increments from the top of each core to 10 cm was calculated. This computation involved summing the volume of each burrow located within each 2 cm
depth interval. Results are presented from the April cruise (Figure 16) and the September cruise (Figure 17) for all eight CT subcores. According to the April CT results, the highest total burrow volume is located in the 2 to 4 cm increment for province NO, the 0 to 2 cm increment for province BH, the 4 to 6 cm increment for province HO, and the 6 to 8 cm increment for province FH (Figure 16). Only the subcore from province BH follows the pattern predicted by the hypothesis, *ie:* the highest total volume of burrows is located at the top of the subcore. However, as predicted, total volume does decrease with depth in all subcores below the depth interval containing the highest total volume.

According to the September CT results, the highest total burrow volume is located in the 2 to 4 cm increment for province 9NO. The highest total burrow volume is located in the 4 to 6 cm increment for provinces 9BH, 9HO, and 9FH. Total burrow volume decreases below these intervals in each respective subcore (Figure 17).
Figure 16. Total burrow volume as a function of depth in the sediment for April CT subcores. The provinces are designated as NO (normoxic since 2001), BH (hypoxic in 2006 and 2007), HO (hypoxic in 2006, 2007, and 2008), and FH (hypoxic in 2008 and 2009).
Figure 17. Total burrow volume as a function of depth in the sediment for September CT subcores. The provinces are designated as NO (normoxic since 2001), BH (hypoxic in 2006 and 2007), HO (hypoxic in 2006, 2007, and 2008), and FH (hypoxic in 2008 and 2009).

Total Burrow Surface Area

Frequency histograms of April and September burrow surface areas show that the burrow surface area data are all skewed to the right, with the majority of the burrow surface areas ranging from 0.8 mm$^2$ to 100 mm$^2$. The highest relative frequency of burrow surface areas lies between 6 mm$^2$ to 15 mm$^2$ for all subcores (Appendices A, B).

Burrow surface areas were averaged over 1 cm depth intervals from the top of the subcore to a depth of 10 cm for each subcore in order to show how burrow surface area varied with depth in the sediment. April burrow surface areas do not appear to follow a clear trend with respect to depth and vary greatly for each subcore (Figure 18). Average burrow surface areas in subcore NO vary between 5 mm$^2$ and 28 mm$^2$ for the entirety of
the subcore except for the 5 to 6 cm interval, which has an average surface area of about 69 mm$^2$. Average burrow surface areas in subcore BH remain high throughout the top of the subcore (about 42 mm$^2$ to 58 mm$^2$) from 0 to 4 cm sediment depth. Average burrow surface area then drops to about 20 mm$^2$ in the 4 to 5 cm interval, and remains below 20 mm$^2$ until the 9 to 10 cm depth interval, where average surface area increases to about 64 mm$^2$. Average burrow surface area in subcore HO varies between about 6 mm$^2$ and 41 mm$^2$ throughout the subcore. Average burrow surface area in subcore FH remains below 40 mm$^2$ throughout the top 6 cm of the subcore. Average burrow surface area then peaks at about 118 mm$^2$ in the 6 to 7 cm depth interval and decreases to about 34 mm$^2$ at the bottom of the subcore.

September average burrow surface area varies over a narrower range than the April burrow surface areas, when considering the average surface area as a function of depth in the sediment (Figure 19). September average burrow surface areas range from 5 mm$^2$ to 82 mm$^2$, while April average burrow surface areas range from 5 mm$^3$ to 118 mm$^3$. Average burrow surface area in subcore 9NO is consistent throughout the entire subcore, varying from about 5 mm$^2$ to 31 mm$^2$. Average burrow surface area in subcore 9BH ranges from 10 mm$^2$ to 35 mm$^2$ except for two intervals in the subcore, 4 to 5 cm and 7 to 8 cm, where the average surface area increases to about 55 mm$^2$ and 68 mm$^2$, respectively. Average surface area in subcore 9HO varies from 18 mm$^2$ to 58 mm$^2$, except for the peak surface area of about 82 mm$^2$ in the 6 to 7 cm interval. Average surface area in subcore 9FH remains relatively low, varying from 9 mm$^2$ to 25 mm$^2$ and peaking in the depth interval 7 to 8 cm at about 40 mm$^2$. 
Figure 18. Average burrow surface area as a function of depth in the sediment for April CT subcores. The provinces are designated as NO (normoxic since 2001), BH (hypoxic in 2006 and 2007), HO (hypoxic in 2006, 2007, and 2008), and FH (hypoxic in 2008 and 2009).
Figure 19. Average burrow surface area as a function of depth in the sediment for September CT subcores. The provinces are designated as NO (normoxic since 2001), BH (hypoxic in 2006 and 2007), HO (hypoxic in 2006, 2007, and 2008), and FH (hypoxic in 2008 and 2009).

The median, range, and 25th and 75th percentiles for each subcore were calculated in order to characterize the burrow surface area data (Figure 20). Arranged from longest median burrow surface area to shortest median surface area, the CT subcores are as follows: 9HO (18.10 mm²) > HO (17.10 mm²) > 9BH (16.89 mm²) > FH (14.98 mm²) > BH (12.36 mm²) > NO (10.43 mm²) > 9FH (7.87 mm²) > 9NO (6.79 mm²). Of the April subcores, the HO had the greatest median burrow surface area and NO had the least median burrow surface area. Of the September subcores, 9HO had the greatest median burrow surface area and 9NO had the least median burrow surface area. The April subcore with the narrowest range of burrow surface area was HO, and the April subcore with the widest range of burrow surface areas was BH (Figure 20; Table 1). The
September subcore with the narrowest range of burrow surface areas was 9FH, and the September subcore with the widest range of burrow surface areas was 9HO (Figure 20; Table 1).

*Figure 20.* Box-and-whisker plots of April and September burrow surface areas. The provinces are designated as NO (normoxic since 2001), BH (hypoxic in 2006 and 2007), HO (hypoxic in 2006, 2007, and 2008), and FH (hypoxic in 2008 and 2009).
Data Normalization

In order to account for differences in mixing rates and sedimentation rates at the different provinces (Appendix E), an attempt to normalize the burrow abundance and burrow length data was made. Biogenic mixing can destroy burrows, so the greater the mixing rate, the more the census underestimates the relict burrows and the more the census represents the present active benthos. Mixing rates at all four provinces were divided by the mixing rate at the control, province NO, in order to determine the mixing factor, $f_m$. (All calculations were performed separately on April and September data.) Mixing depth was also taken into consideration because below that depth very few burrows are active and a greater proportion of the burrows are relict. The mixing depth at each province was divided by 10 cm, the length of each CT subcore, in order to determine the mixing depth factor, $f_d$. Sedimentation rate can affect burrow abundance and burrow length as well. Sedimentation rates at all four provinces were divided by the sedimentation rate of the control, province NO, in order to determine the burial factor $f_b$. Burrow length data was divided by $f_b$, and burrow abundance data was multiplied by $(f_m \times f_d) / f_b$. Results of the data normalization procedure are presented in Table 2.

Results of the data normalization procedure indicate that province BH has the greatest abundance of burrows in April and that province HO has the lowest abundance of burrows in April. Province HO has the greatest abundance of burrows in September and province FH has the lowest abundance of burrows in September. The normalized burrow abundance data contradicts the stated hypothesis because province NO should have contained the greatest abundance of burrows. The normalized burrow length data, however, does not contradict the stated hypothesis. These data show that province BH,
which experienced hypoxia infrequently over the past ten years, has the greatest median length in both April and September and that province FH, which experienced hypoxia the most frequently of all four provinces, has the shortest median length in both April and September.

Table 2

*Normalization of Burrow Abundance and Burrow Length Data.*

<table>
<thead>
<tr>
<th>Subcore</th>
<th>Total Number of Burrows Per Subcore</th>
<th>Normalization Factor (f_m \times f_d \div f_b)</th>
<th>Normalized Total Number of Burrows Per Subcore</th>
<th>Median Burrow Length (mm)</th>
<th>Normalization Factor (f_b)</th>
<th>Normalized Median Burrow Length (mm)</th>
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</thead>
<tbody>
<tr>
<td>NO</td>
<td>111</td>
<td>1.00</td>
<td>111</td>
<td>3.06</td>
<td>1.00</td>
<td>3.06</td>
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<td>BH</td>
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<td>698</td>
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<td>6.71</td>
</tr>
<tr>
<td>HO</td>
<td>58</td>
<td>1.02</td>
<td>59</td>
<td>4.64</td>
<td>2.89</td>
<td>1.61</td>
</tr>
<tr>
<td>FH</td>
<td>105</td>
<td>2.08</td>
<td>218</td>
<td>4.15</td>
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<td>1.21</td>
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<tr>
<td>9BH</td>
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<td>841</td>
<td>5.76</td>
<td>0.55</td>
<td>10.47</td>
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<tr>
<td>9HO</td>
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<td>1570</td>
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<td>9FH</td>
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<td>0.26</td>
<td>42</td>
<td>2.90</td>
<td>3.55</td>
<td>0.82</td>
</tr>
</tbody>
</table>
CHAPTER IV
DISCUSSION

The Effect of Hypoxia on the Number of Burrows in Marine Sediment Cores

According to the results, province NO had a greater number of burrows in the top 10 cm of the core than any of the other three provinces in both April and September. This was in accordance with the hypothesis, which suggested that benthic macrofauna communities exposed less frequently to hypoxia would have more burrow structures than communities exposed more frequently to hypoxia. However, the site with the second highest number of burrows in both April and September was province FH, the province that was recently and more frequently exposed to hypoxia in the last ten years. Provinces BH and HO, which were exposed to hypoxia but less frequently than province FH, had the least number of burrows per core in both April and September.

It is possible that relict burrows (i.e. abandoned tubes with no connection to the sediment-water interface) were detected in the present study. A similar result was documented by Rosenberg and Ringdahl (2005), who used CT to study biogenic structures in marine sediments on the Swedish Skagerrak coast. Three stations differing in their exposure to hypoxia were chosen for the study. One of the stations (118) was in the process of recovering from a previous hypoxic event. At station 118, Rosenberg and Ringdahl found few biogenic structures but a large number of benthic macrofaunal species present. At this time, it was also found that the greatest number of polychaete tubes occurred deeper in the sediment at around 7 to 14 cm. The authors suggested that the tubes were relict and had become disconnected from the sediment-water interface by bulldozing sea urchins (Rosenberg and Ringdahl, 2005). Five years later, the number of
biogenic structures found at the recovering site exceeded that of the reference site, which had been undisturbed by hypoxia (Rosenberg et al., 2007). The authors explained that during hypoxia, organic matter was accumulating, and bioturbation and aerobic respiration increased following water column re-oxygenation.

In the present study, it was not possible to differentiate between inhabited and relict burrows because abandoned burrows may persist for an unspecified amount of time, based on biological and physical mixing rates. Therefore, the census of burrow structures is an integration of bioturbation over an unspecified amount of elapsed time. The comparison of burrow censuses among the four provinces would be considered straightforward if each of the four provinces experienced the same amount of sedimentation, erosion, and biological mixing during the elapsed time. According to measurements of sedimentary organic carbon and sedimentation rate in April and September of 2009, province FH receives a higher volume of organic matter and sediment input compared to the other three provinces because FH is located closest to the mouth of the Mississippi River (Yeager, 2010). So, it is possible that accumulated organic matter may have boosted early (pre-hypoxic) biological activity. Furthermore, the higher sedimentation at province FH may have preserved more relict burrows.

Another possible explanation for why the FH core had more burrows than the BH or HO cores could be that the oxygen concentration at province FH was not low enough to affect the macrofaunal community and some other outside influence could be the cause. For example, in a study by Belley et al. (2010) at the Estuary of St. Lawrence, Canada, high densities of sea urchins were found at a hypoxic site. Belley et al. (2010) photographed the seabed of the Estuary of St. Lawrence during the summers of 2006 and
2007 and identified visible traces of bioturbation on the seafloor and benthic macrofauna. Contrary to their expectations, Belley et al. found that there were higher densities of bioturbation traces in hypoxic regions than in well-oxygenated regions. They attributed this finding to the possibility that the oxygen concentrations were not low enough at the hypoxic sites to cause significant differences in bioturbation activity attributed to the fauna creating the traces. They also mentioned the possibility that the surface-deposit-feeding brittle star, *Ophiura* sp., which has an “active feeding mode,” could be the cause of the high density of bioturbation traces in the hypoxic region (Belley et al., 2010).

The Effect of Hypoxia on Macrofaunal Burrow Length, Volume, Surface Area, and Diameter in the Northern Gulf of Mexico

According to the stated hypothesis, sediments impacted most recently by hypoxia should contain macrofaunal burrows that are shorter in length, smaller in diameter, smaller in volume, and smaller in surface area. Sediments not impacted, or impacted less recently, by hypoxia should contain macrofaunal burrows that are longer, larger in diameter, larger in volume, and greater in surface area. However, results indicate that the CT subcore from province HO, which was recently affected by hypoxia, contained the longest burrows and the highest median volume and surface area in burrows for both April and September 2009. Moreover, the CT subcore from province NO, which was unaffected by hypoxia, contained the shortest burrows and the lowest median volume and surface area in burrows for both April and September 2009. Burrow diameter was largest in FH and HO provinces in April and BH and HO provinces in September.

There is a good correlation between the four burrow parameters, such that the province (HO) with the longest burrow length also has the largest burrow diameter, and
thus the largest burrow volume and surface area; conversely, the province (NO) with the shortest burrow length has the smallest burrow diameter, and thus the smallest burrow volume and surface area. The provinces between the two extremes correspond accordingly. However, there does not appear to be a correlation with burrow parameters and depth in the sediment.

A possible reason why the subcore from province HO contained the longest burrows with the greatest median volume and surface area could be that this site is in a recovery stage from hypoxia, and a number of factors are at work here. A similar study conducted by Rosenberg et al. (2007) calculated the volume occupied in sediment cores by biogenic structures at three stations differing in exposure to periodic hypoxic events on the Swedish Skagerrak coast. Their results indicated that the station recovering from a recent hypoxic event had the greatest number of animals and the largest volume occupied by biogenic structures. Rosenberg et al. (2007) concluded that benthic fauna recovering from previous hypoxic events can establish burrows with greater volumes and probably with greater impact on biogeochemical processes than benthic fauna inhabiting sites with more stable environmental conditions.

Macrofauna abundance data collected for a study of the effects of hypoxia by Kevin Briggs at the Naval Research Laboratory (NRL) indicate that province HO did have a high density of macrofaunal organisms in April 2009 and an even higher density in September 2009 (Appendix D). Furthermore, the bioturbation rate, as determined by sediment mixing rates of $^{234}$Th$\beta$ calculated by Kevin Yeager at the University of Southern Mississippi for the NRL hypoxia study, at province HO was the highest of the four provinces in September 2009 (Appendix E). The highest bioturbation rate of
province HO in September 2009 coincides with the highest values for burrow length, volume, and surface area. These results suggest that province HO was in an active phase of recovery from hypoxia during 2009.

There appears to be a correlation between bioturbation rate and burrow length, volume, and surface area. Provinces FH, BH, and HO had the highest rates of bioturbation and the highest median values of burrow length, volume, and surface area in April. Province HO had the highest rate of bioturbation in September, followed in order by provinces BH, FH, and NO. The measurements of burrows from CT subcores collected in September indicated that the highest median lengths, volumes, and surface areas followed this same trend, with province HO having the highest overall median value, followed in order by provinces BH, FH, and NO. The bioturbation rate was not correlated with median burrow diameter.

Results indicated that province NO contained the greatest number of burrows in both April and September, but also the shortest burrows with the lowest median volume and surface area. One possible explanation could be that province NO is inhabited by a benthic infaunal community dominated by macrofauna with a smaller average body size than the other provinces. Other studies show that burrowing depth is dependent on body size with larger organisms constructing deeper and longer burrows (Mazik et al., 2008). However, larger-bodied infauna such as crustaceans and echinoderms are typically more sensitive to hypoxia than smaller taxa such as polychaetes, sipunculids, mollusks, and cnidarians (Levin et al., 2009). Studies discussing the diversity of the benthic communities at the four provinces will be better able to address this aspect of the research.
The sediment at province NO was primarily composed of silty-clay but the sediment at this province also contained the highest percentage of gravel-size material of all four provinces (Appendix F). In a similar CT study, researchers found a correlation between the quantity of coarse gravel material in sediment cores and the space occupied by biogenic structures (Mermillod-Blondin et al., 2003). Specifically, Mermillod-Blondin et al. determined that lower space occupation by biogenic structures correlated with a high quantity of gravel from 90 to 140 mm in one of their sediment cores, whereas the other cores had lower quantities of coarse materials and a higher percentage of space occupied by biogenic structures (2003). The high percentage of sand and shell material in the NO subcores may explain why the length, diameter, volume, and surface area of the macrofaunal burrows at province NO were lower than in the other three provinces.

The normalized burrow length data shows that province BH, rather than province HO, had the longest median burrow lengths and that province FH, rather than province NO, had the shortest median burrow lengths. These results agree with the stated hypothesis because provinces experiencing hypoxia more frequently (FH) are expected to contain shorter burrows and provinces experiencing hypoxia less frequently (BH) are expected to contain longer burrows. These results agree with the Pearson and Rosenberg model.

The Effect of Hypoxia on the Depth of Macrofaunal Burrows

According to previous studies, the total volume occupied by biogenic structures in marine sediment cores tends to be the highest in the upper few centimeters of sediment and to gradually decrease with depth (Belley et al., 2010; Mazik et al., 2008; Mermillod-Blondin et al., 2003; Michaud et al., 2003). In this study, the highest total volume was
located in depth intervals above 6 cm in all CT subcores except for the subcore from province FH from April. The highest total burrow volume of the April FH subcore was located in the 6 to 8 cm interval and decreased in the 8 to 10 cm interval.

In studies by Mermillod-Blondin et al. and Michaud et al. in 2003, sediment cores were retrieved from an intertidal flat in the St. Lawrence estuary, which was unaffected by hypoxia but which had experienced an intense flash flood in 1996. The purpose of these studies, respectively, was 1) to determine the impacts of sedimentary deposition on benthic fauna and 2) to use CT to measure the space occupied by benthic fauna (Mermillod-Blondin et al., 2003; Michaud et al., 2003). The CT images were processed using the medical program Osiris in order to quantify the space occupied by biogenic structures versus depth. Biogenic structures were identified from CT images by using tomographic intensity to distinguish between benthic structures and the surrounding sediments. Mermillod-Blondin et al. found that the total volume occupied by biogenic structures was highest at the sediment-water interface and decreased with depth (2003). Michaud et al. concluded that colonization by benthic fauna is closely linked to the stability of the sediment column and that biogenic structures were quickly formed after erosion events occurred (2003).

The current study showed that the total volume occupied by biogenic structures was highest below the sediment-water interface. These results may indicate that the high volume of burrow structures in the 2 to 6 cm depth interval is representative of relict burrows, which would not be connected to the surface of the subcore. A similar result was found by Rosenberg and Ringdahl in 2005, when researchers reported that burrow volumes were greatest at the surface and gradually declined with depth at the station
currently experiencing hypoxia, but not at the station being re-colonized after a hypoxic event where burrow volume was greatest deeper in the sediment, at 7 to 14 cm. The authors explained that relict tubes could have caused this increase in volume (Rosenberg and Ringdahl, 2005). The presence of relict burrows could explain why the April FH subcore had the highest total burrow volume in the 6 to 8 cm depth interval. The April BH subcore was the only subcore with the highest total burrow volume in the top 0 to 1 cm interval. It is interesting to note that province BH had the highest density of animals of all of the four provinces in the top 0 to 2 cm depth interval in April (Appendix D). The high density of animals in this depth interval should relate to a high volume of burrow structures in the same depth interval.

Seasonal Variation of Burrow Parameters

The total number of burrow structures found in CT subcores at each province increased from April to September of 2009. These results suggest that despite the presence of hypoxia during the growing season between April and September, macrofauna reproduce, multiply, and become more active. The bioturbation rate increased by at least five-fold at all provinces from April to September (Appendix E). Bioturbation depth also doubled from April to September at all provinces except province FH, which stayed the same (Appendix E).

Province HO contained the longest burrows with the highest median volume and surface area in both April and September, whereas province NO contained the shortest burrows with the lowest median volume and surface area in both April and September. This may indicate that the benthic faunal communities at the four provinces are relatively adapted to their respective environments. The lengths, volumes, and surface areas of
burrows at these provinces did not vary significantly at the same province between April and September 2009.
CHAPTER V

CONCLUSIONS

1) The computed tomography subcore taken from the site unaffected by hypoxia (NO) contained the highest abundance of burrow structures in both April and September, as was expected. However, the site with the second highest number of burrows in both April and September was a site that had frequently experienced hypoxia (FH). This finding is attributed to the proximity of the site to the mouth of the Mississippi River, which deposits high volumes of organic matter and sediment into the region, causing an increase in bioturbation activity following water column re-oxygenation. Furthermore, a high sedimentation rate helps to preserve relict burrows that are abandoned by macrofauna in the sediment.

2) The CT subcore taken from the province that experienced hypoxia in 2006, 2007, and 2008 (HO) contained significantly longer burrows with greater median volumes, surface areas, and diameters in both April and September than burrows at any of the other three provinces. Previous studies found that benthic fauna recovering from hypoxic events can establish burrows with greater volumes than at stations with more stable environmental conditions. It is possible that the benthic community at province HO is in a state of recovery. Furthermore, macrofauna abundance data indicate that province HO had a high abundance of macrofaunal organisms and the highest bioturbation rate of all four provinces in September 2009, which could help account for the large burrows at this site.

3) Province NO contained the greatest number of burrows in both April and September, but also the shortest burrows with the lowest median volume and surface
area. Province NO contained the second highest abundance of macrofauna of all four provinces in April and the highest abundance of macrofauna in September. This could account for the high abundance of burrows in the NO subcore. However, the CT subcores from province NO contained a high percentage of gravel-size material. There appears to be an inverse relationship between percentage of gravel-size material and burrow size.

4) The greatest total volume occupied by biogenic structures was located in depth intervals above 6 cm in all CT subcores except for the subcore collected in April from the province that experienced hypoxia in 2008 and 2009 (FH). A high volume of burrows in the top 6 cm is most likely correlated with the high abundance of animals in these depth intervals. The highest total burrow volume of the April subcore from province FH was located in the 6 to 8 cm interval but decreased in the 8 to 10 cm interval. The presence of relict burrows could explain why this CT subcore had the highest total burrow volume in the 6 to 8 cm depth interval.

5) The total number of burrows found in CT subcores at each province increased from April to September of 2009. Also, the bioturbation rate increased by at least five-fold at all provinces from April to September. Bioturbation depth doubled from April to September at all provinces, except the province that was hypoxic in 2008 and 2009 (FH), which stayed the same. These results suggest that despite the presence of hypoxia during the growing season between April and September, macrofauna reproduce, multiply, and become more active.

6) Median burrow lengths were significantly greater in the April CT subcores taken from the normoxic province (NO) and the province that experienced hypoxia in 2008 and 2009 (FH) than in the September CT subcores collected at the same provinces.
Median burrow lengths were significantly lower in April than in September at provinces BH and HO. Median burrow diameters were significantly greater in April than September at provinces NO, FH, and BH. There was not a significant difference in median burrow diameter at province HO between April and September. In September, province HO had the longest burrows with the largest diameters out of all CT subcores collected in both April and September. Also in September, province NO had the shortest burrows. This seems to indicate that there is a lot of variability between the four provinces in terms of biogenic activity and possibly macrofaunal community composition. It is also possible that increased biological mixing in September disturbed biogenic burrow structures that had been present in April.

7) The normalized burrow length data accounting for differential mixing and sedimentation shows that province BH, rather than province HO, had the longest median burrow lengths and that province FH, rather than province NO, had the shortest median burrow lengths. These results agree with the stated hypothesis because provinces currently experiencing hypoxia (FH) were expected to contain shorter burrows and the province experiencing the longest recovery time from hypoxia (BH) was expected to contain longer burrows than provinces experiencing hypoxia more recently.

8) These conclusions could be made more robust by including the analysis of more CT subcores, resulting in a more stable estimate of burrow abundance and burrow dimensional parameters at the four provinces. A complementary study investigating the diversity of macrobenthos at the four provinces will identify the active bioturbating infauna in the region and will help explain how hypoxia has affected the benthic communities in the northern Gulf of Mexico.
APPENDIX A

RELATIVE FREQUENCY HISTOGRAMS OF APRIL 2009

BURROW PARAMETER DATA

Frequency Histogram of Province FH Burrow Lengths
Frequency Histogram of Province HO Burrow Surface Area

Frequency Histogram of Province NO Burrow Lengths
Frequency Histogram of Province NO Burrow Surface Areas

Frequency Histogram of Province BH Burrow Lengths
Frequency Histogram of Province BH Burrow Diameters

Frequency Histogram of Province BH Burrow Volumes
Frequency Histogram of Province BH Burrow Surface Areas
APPENDIX B

RELATIVE FREQUENCY HISTOGRAMS OF SEPTEMBER 2009

BURROW PARAMETER DATA

Frequency Histogram of Province FH Burrow Lengths
Frequency Histogram of Province FH Burrow Diameters

Frequency Histogram of Province FH Burrow Volumes
Frequency Histogram of Province FH Burrow Surface Areas

Frequency Histogram of Province HO Burrow Lengths
Frequency Histogram of Province NO Burrow Surface Areas

Frequency Histogram of Province BH Burrow Lengths
Frequency Histogram of Province BH Burrow Diameters

Frequency Histogram of Province BH Burrow Volumes
APPENDIX C

2D IMAGES OF COMPUTED TOMOGRAPHY SUBCORES PRODUCED IN IMAGEPRO PLUS

Figure 1. Black and white image of April CT subcore from province FH.
Figure 2. Color image of April CT subcore from province FH.
Figure 3. Black and white image of April CT Subcore from province HO.
Figure 4. Color image of April CT Subcore from province HO.
Figure 5. Black and white image of April CT subcore from province NO.
Figure 6. Color image of April CT subcore from province NO.
Figure 7. Black and white image of April CT subcore from province BH.
Figure 8. Color image of April CT subcore from province BH.
Figure 9. Black and white image of September CT subcore from province FH.
Figure 10. Color image of September CT subcore from province FH.
Figure 11. Black and white image of September CT subcore from province HO.
Figure 12. Color image of September CT subcore from province HO.
Figure 13. Black and white image of September CT subcore from province NO.
Figure 14. Color image of September CT subcore from province NO.
Figure 15. Black and white image of September CT subcore from province BH.
Figure 16. Color image of September CT subcore from province BH.
APPENDIX D

INFAUNAL ABUNDANCE (NUMBER OF ANIMALS PER SQUARE METER) AT EACH PROVINCE DURING APRIL AND SEPTEMBER 2009. DATA PRODUCED BY KEVIN BRIGGS AT THE NAVAL RESEARCH LABORATORY.

<table>
<thead>
<tr>
<th>Subcore</th>
<th>Depth Interval</th>
<th>0–2 cm</th>
<th>2–4 cm</th>
<th>4–6 cm</th>
<th>6–8 cm</th>
<th>8–10 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO</td>
<td>7453</td>
<td>2607</td>
<td>968</td>
<td>624</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>BH</td>
<td>9623</td>
<td>1264</td>
<td>640</td>
<td>343</td>
<td>203</td>
<td></td>
</tr>
<tr>
<td>HO</td>
<td>5658</td>
<td>2279</td>
<td>687</td>
<td>437</td>
<td>312</td>
<td></td>
</tr>
<tr>
<td>FH</td>
<td>2692</td>
<td>1233</td>
<td>593</td>
<td>406</td>
<td>203</td>
<td></td>
</tr>
<tr>
<td>9NO</td>
<td>6792</td>
<td>1951</td>
<td>843</td>
<td>421</td>
<td>187</td>
<td></td>
</tr>
<tr>
<td>9BH</td>
<td>2919</td>
<td>858</td>
<td>359</td>
<td>125</td>
<td>218</td>
<td></td>
</tr>
<tr>
<td>9HO</td>
<td>3894</td>
<td>1061</td>
<td>702</td>
<td>578</td>
<td>234</td>
<td></td>
</tr>
<tr>
<td>9FH</td>
<td>4019</td>
<td>1795</td>
<td>671</td>
<td>656</td>
<td>500</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX E

SUMMARY OF BIOTURBATION AND SEDIMENTATION ACCUMULATION DATA FROM APRIL AND SEPTEMBER 2009. DATA PRODUCED BY KEVIN YEAGER AT THE UNIVERSITY OF SOUTHERN MISSISSIPPI.

<table>
<thead>
<tr>
<th>Subcore</th>
<th>Bioturbation Depth (cm) $^{234}$Th$_{ss}$</th>
<th>Bioturbation Coefficient ($D_b$, cm$^2$/y) $^{234}$Th$_{ss}$</th>
<th>$^{210}$Pb$_{ss}$ Sediment Accumulation Rate (cm/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO</td>
<td>1.75</td>
<td>2.15</td>
<td>0.09 ± 0.03</td>
</tr>
<tr>
<td>BH</td>
<td>1.75</td>
<td>8.32</td>
<td>0.05 ± 0.01</td>
</tr>
<tr>
<td>HO</td>
<td>2.25</td>
<td>4.91</td>
<td>0.26 ± 0.13</td>
</tr>
<tr>
<td>FH</td>
<td>2.75</td>
<td>9.78</td>
<td>0.31 ± 0.21</td>
</tr>
<tr>
<td>9NO</td>
<td>3.50</td>
<td>53.00</td>
<td>0.22 ± 0.02</td>
</tr>
<tr>
<td>9BH</td>
<td>4.50</td>
<td>128.13</td>
<td>0.12 ± 0.05</td>
</tr>
<tr>
<td>9HO</td>
<td>3.50</td>
<td>519.76</td>
<td>0.22 ± 0.05</td>
</tr>
<tr>
<td>9FH</td>
<td>2.75</td>
<td>62.58</td>
<td>0.78 ± 0.07</td>
</tr>
</tbody>
</table>
APPENDIX F

PERCENTAGE OF GRAVEL (GRAIN SIZE >2 MM) PRESENT AT EACH PROVINCE. DATA FROM GRAIN SIZE ANALYSES PERFORMED AT THE NAVAL RESEARCH LABORATORY.

<table>
<thead>
<tr>
<th>Province</th>
<th>Depth Interval</th>
<th>0–2 cm</th>
<th>2–4 cm</th>
<th>4–6 cm</th>
<th>6–8 cm</th>
<th>8–10 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO</td>
<td></td>
<td>0.78</td>
<td>1.40</td>
<td>2.79</td>
<td>3.31</td>
<td>4.06</td>
</tr>
<tr>
<td>BH</td>
<td></td>
<td>0.01</td>
<td>0.75</td>
<td>0.16</td>
<td>0.04</td>
<td>0.11</td>
</tr>
<tr>
<td>HO</td>
<td></td>
<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
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