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Laboratory and field measurements of bioturbation by macrofauna in a coastal setting

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LABORATORY AND FIELD MEASUREMENTS OF BIOTURBATION BY
MACROFAUNA IN A COASTAL SETTING

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

The Department of Oceanography and Coastal Sciences

by
Skyler-Bree Kiernan Neylon
B.S., George Mason University, 2003
May 2006

FOR DAD

LET'S BELIEVE
in
BABY STEPS TO A BETTER WORLD

ALL MY LOVE TO MOM, BEAUXREGARD, AND SUMMER MAGIC

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I wish to extend my gratitude to my mentor, Dr. Sam Bentley, a gifted scientist and personal and professional role model, whose guidance, suggestions, insights, careful explanations, and overall zen attitude have aided tremendously in the successful completion of this project. My committee members, Dr. Bob Carney and Dr. Jeff Hanor have also offered individual suggestions and insights which have guided the research.

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ABSTRACT

Two ophiuroid species, *Hemipholis elongata* and *Ophiophragmus spp.* were studied in laboratory microcosms to elucidate patterns of sediment mixing for key bioturbators in the Mississippi Sound, Mississippi. The effects of bioturbation on artificially stratified sediments in microcosms were traced via time-series digital x-radiography. Preliminary results indicate that for three population densities of the brittle stars (comparable to field densities), a steady state volumetric bioturbation rate of 1-2 cm³/d is reached within two months of introduction to a fresh system. The preservation quotient, *q*, a fractional measure of preserved primary fabric, reached a minimum of 0.5 during the 16-week experiment. Maximum depth of bioturbation appears to be inversely proportional to population density in these species, with individuals in sparser populations also being less mobile. Thus, greater dispersive mixing occurs to shallower depths in sediments hosting greater population densities. In addition, bioturbation rates appear to decrease exponentially with depth, with volumetric reworking at the base of the mixed layer being approximately 1×10^{-3} those at the surface. Field measurements after event layer deposition showed that re-colonization by the original key bioturbators was not immediate and a lag time of at least 8 months may be valid for future modeling attempts in similar settings.

INTRODUCTION

A. General Background and Significance

In marine and estuarine systems, the interface between sediment and water is commonly referred to as the benthic boundary layer (BBL) and represents a zone of the biosphere occupied by abundant and diverse life. Bioturbation is a process by which a living organism displaces particulate matter that makes up soil or sediment (Richter 1952), and it actively mixes the water and sediments within the BBL. Bioturbation may be caused by micro- or macroscopic organisms; within the macroscopic life forms, either plants or animals may be the “sediment stirrers”. Bioturbation was first discussed in scientific literature by Charles Darwin (1896), who demonstrated experimentally that earthworms could move and sort soil particles. However, its significance as a field of study remained undeveloped until more recent years, when the effects of macrofauna on diagenesis (Berner 1980), water content, sedimentary fabric, compaction, and seafloor shear strength were acknowledged (e.g. Rhoads and Boyer 1982). Additionally, bioturbation, especially in the form of trace fossils in the geologic record, became of interest in the field of paleoecology (Frey 1975).

Study of event layer sedimentation in modern systems yields much information that can be used in paleoecological reconstructions and has historically been concentrated on such phenomena as storms, floods, and turbidity currents or submarine mudslides. Events like these often leave signals such as differences in grain size, sediment chemistry, and pore-water chemistry. These tracers, or simply the physical structure and fabric of sediments, may be visually apparent when the sediment is examined using x-radiography or other imaging techniques. For example, in a near shore environment, a thick mud lens may be sandwiched between two sandy fining upward sequences. This mud lens may be categorized as an event layer in light of its thickness and its differing grain size, porosity and mineral composition, especially

if it may be linked with a historic sediment transport event. Post deposition, the layer may be reworked by burrowing infauna, and subsequent sampling of the sediment column may then reveal mottling and distortion (e.g. Dott and Bourgeois 1982).

Beginning with Moore and Scruton (1957), many researchers have studied relations between sedimentation, bioturbation and resultant ichnofabric. Most such studies, excepting important recent work (e.g. Bentley and Sheremet 2003), have been largely descriptive and lacking a quantitative element. In contrast, quantitative, particularly diffusive, modeling has been the primary vehicle toward quantitative understanding of chemical diagenesis since it allows for the incorporation of the many variables that influence sedimentary alterations (e.g. Berner 1980; Boudreau 1986(a), 1986(b)). Such quantitative geochemical models can take into account the downward advection of the sediment as new deposition occurs, the diffusion of chemical tracers through the sediment column, and mixing processes that take place at the seafloor. The general diagenetic equation is shown below.

$$\frac{\partial C_i}{\partial t} = \frac{\partial}{\partial z} \left(D \frac{\partial C_i}{\partial z} \right) - \frac{\partial (vC_i)}{\partial z} + \sum R_i$$

In this equation, C represents the concentration of a tracer of interest, t is time, z is depth in the sediment column, D is the diffusion coefficient, v is the rate of deposition, and the final term of the equation represents any additional reactions, chemical or radiochemical, which the tracer undergoes. It is the intent of this research to isolate the mixing component of diagenesis, usually described with the diffusion term, as it is caused by burrowing brittle stars, and to describe it quantitatively using measurements from field and laboratory studies.

At the present time, bioturbation effects on most sediments are most commonly described using the biodiffusion coefficient, D_b , in units of length squared over time (Berner 1980).

However, in light of behavior such as conveyor belt feeding, during which benthos feed at

subsurface levels and excrete material at the surface, other models treat bioturbation as advective since particles may be displaced vertically several cm during the process (e.g., Rice 1986). Further, most models that seek to quantify bioturbation rely on steady state simplifications, at the expense of some important traits of many near shore environments, viz., non-steady state deposition caused by sporadic events such as storms (e.g., Keen et al. 2004), floods (Bentley and Nittrouer 2003), submarine mudslides (Kneller and Branney 1995), and seismic activity (e.g., Bryant et al. 1992). The assumption of steady state deposition also limits the paleoecological application of the models that have been developed because sedimentation rates in many shelf settings are rarely constant, thus violating steady state assumptions. Episodically created sedimentary event layers make up a significant portion of the sediment inventory in many coastal settings (e.g., Velardo et al. 2003). Thus, accurate interpretations of the sediment record must allow physical and chemical sedimentary properties to vary in a non-steady state fashion to account for event deposition.

Recent attempts to model these process interactions have sought to incorporate more realistic process descriptions (Boudreau et al 2001; Bentley and Sheremet 2003; Bentley et al. in press). Even so, required simplifications in these attempts to model bioturbation are many. The process of teasing apart biological reworking and event sedimentation may yield plentiful information for research focused on paleotempestology, or the study of old storms, which is used for predictive modeling in many climate change scenarios. The present study evaluates some biogenic impacts on the evolution of event layers with the expectation of finding that: (1) depth-dependent reworking occurs with intensities highest at the surface and lowest at the base of the mixed layer; (2) burrowing by these brittle stars is the cause of the mottling that is often recovered in sediment samples that straddle periods of event deposition; and (3) that mixing intensity is directly proportional to their population density.

It is a goal of this research to study the preservation of small-scale stratification generated by episodic sedimentation and mixed by burrowing macrofauna. Three specific approaches are used: time-series x-radiography, event layer study, and stratigraphic modeling using a recently published quantitative numerical method for evaluating event layer preservation in response to benthic activity. To meet this end, a laboratory experiment was conducted using two species of deposit- and filter-feeding brittle stars characteristic of populations found in the Mississippi Sound study area. *Ophiophragmus*, *spp.* and *Hemipholis elongata* were collected and observed using digital x-radiography for 16 weeks in artificially stratified sediments to evaluate reworking rates, maximum bioturbation depth, and mixing patterns. Also, a field survey was conducted ~3 weeks after the landfall of Hurricane Ivan on the Mississippi coast to collect sedimentological evidence for the storm and results from field and lab measurements were applied to the Bentley and Sheremet (2003) model to estimate future preservation of the Ivan-induced event layer.

B. Study Area

The Mississippi Sound, Mississippi, located along the northern coast of the Gulf of Mexico, presents an ideal location for study of event layer diagenesis because: (1) Atlantic hurricanes pass near enough to create significant, distinct event beds with some frequency (Bentley et al. 2000, 2002; Velardo et al. 2003; Keen et al. 2004), and (2) it is occupied by abundant benthic macrofauna. Modern hurricane layer preservation has recently been studied here (Velardo et al 2003; Bentley et al 2000), background sedimentation processes have been investigated (Ludwick 1964) and a bioturbating benthic infauna has been well studied (e.g. Valentine 1991; Furukawa et al 2001). The longitudinally elongate, bar-built estuary is bounded at its northern edge by coastal Mississippi and Alabama, at its southern edge by the Gulf Islands National Seashore barrier islands, at the east by Mobile Bay, and at the west by the St. Bernard lobe of the Mississippi Delta (Figure 1). It covers approximately 4,800 km², over 90% of which

is considered coastal wetland (USEPA 1999). With the exception of inter-island sands, the system is comprised mainly of sandy muds (Ludwick 1964; Velardo 2004).

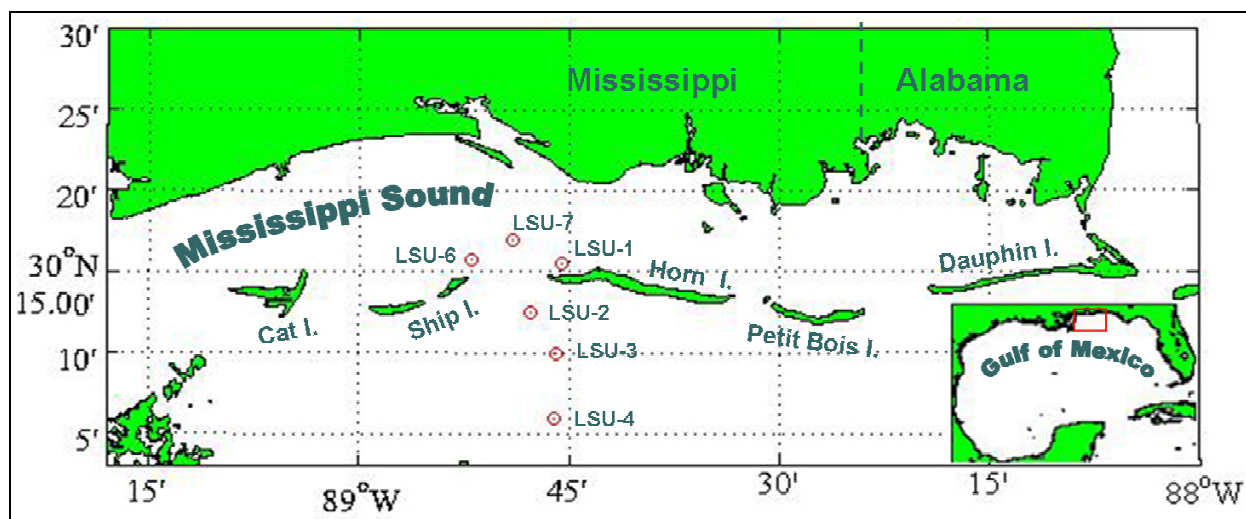


Figure 1: Mississippi Sound study area, along northern Gulf of Mexico coast. Seven coring stations visited during MI 1004 sampling trip. Stations 1-4, 6 & 7 correspond with box cores BC-2, BC-5, BC-7, BC-12, and BC-13, respectively.

The frequent yet variable event sedimentation in the study area is a result of Atlantic hurricanes, which often enter the Gulf of Mexico and make landfall on its northern coast. The 2005 hurricane season, the longest and most severe on record, consisted of 29 named storms and 14 hurricanes (NOAA 2005). Of these, three major hurricanes (Dennis, Katrina, and Rita) made landfall in the Northern Gulf of Mexico. The 2004 hurricane season was relatively less active, producing 16 named storms, including 9 hurricanes, only one of which (Ivan) impacted the Northern Gulf Coast (NOAA 2004). Recent literature indicates that over geologic time as much as 74-92 % of the sediment in the estuary may have been derived from storm deposits (Velardo et al 2003).

In addition to being subject to frequent event deposition, the Mississippi Sound invites studies of biological diagenesis due to its abundant benthic macrofauna. Key bioturbators in the region include a well-documented community of brittle stars (e.g. Valentine 1991), the large,

head-down deposit feeding polychaete *Notomastus spp.*, and an elusive population of the hemichordate *Schizocardium spp.* (Furukawa et al 2001). Over the past 5 years, Dr. Sam Bentley and others have accumulated data on population densities of these organisms at several sites within the study area and cumulative, pooled data was used to project locations where organisms would be found and to determine population densities that were appropriate for use in laboratory reconstructions of the environment. A table of these survey results is shown in Appendix 1.

LSU-1 is located within a federally designated wilderness area, which has been guarded from dredging activity since 1978 (Islands 2003) and has thus been occupied by very reliable, though patchy, supply of infauna. *H. elongata* and *Ophiophragmus spp.*, commonly found brittle stars at this site, are key bioturbators in the area and are amenable to laboratory culture. These animals display the same burrowing behaviors in culture and in nature (Christensen and Colacino 2000). They create y-shaped burrows with their oral disks and two arms anchored near the base of the burrow. Three additional arms protrude ~3cm above the sediment-water interface and tube feet which extend from these arms filter overlying seawater and sort surface particles to extract detritus for food. It has been suggested that, in addition to concealment from predators, these animals burrow during daylight hours for the purpose of maintaining a normal position since they have no gravity receptors and a combination of negative light response and positive touch response helps them maintain the normal position (Reese 1966). They move by expanding and contracting their appendages via the water vascular system and can coordinate these movements to facilitate crawling along the seafloor surface when outside of a burrow. The animals used in this study had central disk diameters ranging from 0.3-1 cm and arm lengths ranging from 3-10 cm and are typical of the size found in the Mississippi Sound.

LABORATORY EXPERIMENTS

A. Lab Methods

Rectangular microcosms with finished dimensions of 25x25x5 cm were constructed of 0.47 cm thick Plexiglas® to create a sediment surface area of 125 cm². Each of eight microcosms was filled with alternating layers of 5 cm-thick Mississippi Sound mud and sand. Sand layers were composed of magnetite sand (top) and builders' sand (2nd from top) alternating to a fourth layer of sand (Figure 2). In the experiments, the sand layer conceptually represent the basal portions of event layers while the top sand layer acted as a convenient tracer of downward mixing. Microcosms were equilibrated with respect to surrounding water and sediments were allowed to consolidate as a function of gravity for three weeks in 100-L tanks filled with 29 ppt water made with Instant Ocean® and kept at 28°C. As necessitated by splashing and evaporation, water levels were maintained throughout the course of the experiments by addition of tap water that had been de-chlorinated by diffusion after resting for at least 2 days in a 200-L plastic drum. Air lifts and siphons circulated water through an external tank filled with CaCO₃ gravel to maintain appropriate pH and provide biological and physical filtration. The airlift filter also provided circulation to facilitate aeration. After the 3-week settling period, organisms were introduced into the microcosms by placing them on the surface of the upper magnetite layer. Table 1 shows the distribution and characteristics of the organism in each microcosm. Animals were fed Tetra® flakes bi-weekly.

Table 1: Distribution of brittle stars in microcosms

Microcosm	1	2	3	4	5	6	7	8
No. organisms	2	2	4	4	7	7	0	0
No. <i>H. elongata</i>	2	2	3	3	5	5	0	0
No. <i>Ophiophragmus</i>	0	0	1	1	2	2	0	0

At weekly intervals, all microcosms were covered with tightly fitting lids, moved a short distance into a frame to assure alignment, and radiographed. The x-ray system was calibrated

prior to each week's x-rays. The PX15-HF Diagnostic x-ray unit was set to 60keV and 32mAs at a beam current of 15mA for imaging. A Thales Flashscan 35 Fine amorphous silicon flat panel digital x-ray detector was used to obtain high-resolution (81.45 pixels per cm) digitized images. Resultant images were saved as 16-bit TIFF (Tagged Image Format Files), 3200 pixels high by 2304 wide.

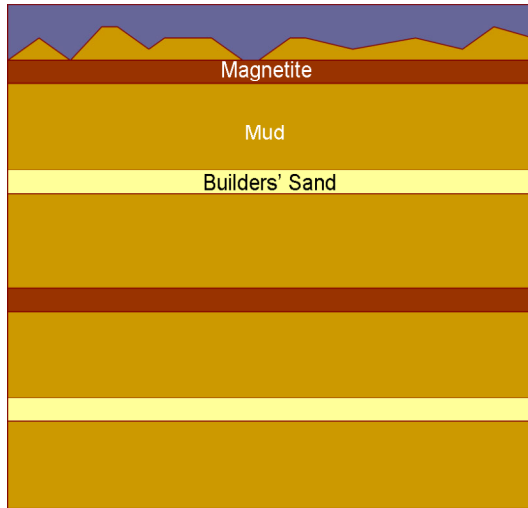


Figure 2: Schematic diagram of uninhabited microcosm viewed from the front

B. Image Analysis

Two methods of image analysis were used and compared: manual digital outlining and automated pixel analysis. For the first method, unmodified TIFF files were processed using MATLAB by first auto-adjusting the pixel intensities to equalize the histogram and improve visibility of individual features within the microcosm. For times t_0 - t_{12} (omitting t_1 ; see Table 1), each image was subtracted from the subsequent one to reveal new structures and mottling. Data regarding whole individual burrows was extracted using the 'bwselect' and 'bwarea' commands in MATLAB to visually outline discrete burrows and some regions of mottling that had developed since the previous week. Area was converted to volume using the average width of reworked regions and assuming square prismatic burrows (Area x Average burrow diameter =

Volume). In reality, the reworked volume from the outlining method is probably best described as a range between a cylinder and a square prism. To convert the calculated volumes here to the volumes of the cylinders which would sit perfectly inside the square prisms, one must simply follow the following formula:

$$V_{\text{cylinder}} = V_{\text{square prism}} * \pi/4 \dots \dots \dots (1).$$

After dividing by elapsed time between x-rays, this treatment of the images yielded depth-integrated bioturbation rates but provided no measure of depth-dependence. Figure 3 shows the contrasted images of representative microcosms from each population density in time-series.

Table 2: Date code for brittle star x-rays

Time	t ₁	t ₂	t ₃	t ₄	t ₅	t ₆	t ₇	t ₈	t ₉	t ₁₀	t ₁₁	t ₁₂
Elapsed days	1	7	14	21	28	34	42	56	70	84	98	112

In the second method, depth-dependent data were extracted by first cropping all raw x-radiographs from a microcosm to the maximum regional extent of activity at the end of the experiment. Each cropped image was then sliced into 40 horizontal sections, such that each discrete depth interval (Δz) measured within the range of 1.98 to 3.91mm according to Table 3.

Table 3: Thickness of horizontal slices in cropped images

Microcosm	1	2	3	4	5	6
Δz (mm)	3.56	2.50	3.91	2.54	1.98	2.45

Next, the pixel intensity was averaged across each depth interval so that changes in pixel intensity with depth could be noted through time. The primary assumption in the automated image analysis is that changes in pixel value are proportional to alteration of the sedimentary fabric via bioturbation, due to particle transport of mud (low pixel intensity) and sand (high pixel

intensity). The assumption was validated by shooting x-rays of a “blank” microcosm fitted with known thicknesses of water- and then magnetite-filled plastic cylinders of known dimensions.

The relationship between fluid-filled tube thickness and pixel intensity was found to be:

$$\bar{I}_{pix} = -317d_{irr} + 12317 \quad (R^2=0.8515).....(2),$$

where \bar{I}_{pix} is the average pixel intensity and d_{irr} is the thickness in cm of water in an open burrow. The relationship between magnetite particles in mud (mixing intensity) and pixel intensity was found to be:

$$\bar{I}_{pix} = 786\ln(d_{mag}) + 13282 \quad (R^2=0.9626).....(3),$$

where d_{mag} is the thickness in cm of magnetite through a mud layer. All values of d were calculated using Equation 2 for $\bar{I}_{pix} < 12500$ and Equation 3 for all other values of \bar{I}_{pix} .

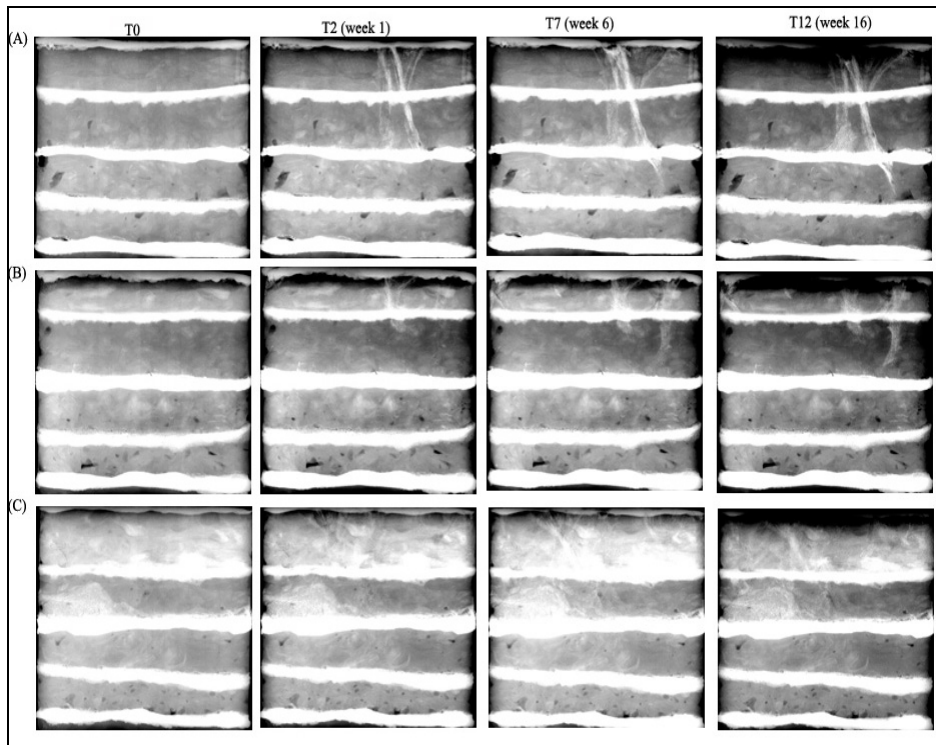


Figure 3: Time-series sub-sample of digitally contrasted and brightened x-rays. Low, medium, and high density populations contain 2, 4, and 7 brittle stars per microcosm, respectively. (A) Low density (microcosm 1); (B) Medium density (microcosm 4); (C) High density (microcosm 6)

Multiplying d by the thickness (in cm) of the slice and the width (cm) of the cropped image yielded the volume of non-mud particles in mud. For times t_0 - t_{12} (omitting t_1), each volume value was subtracted from the subsequent one to yield volumetric change, which was then divided by elapsed time to produce a mixing rate within the animals' range of motion. Thus, by supplying the average pixel intensity over a horizontal slice in an x-radiograph vertical particle displacement per time in that depth interval was estimated, which in turn was related to bioturbation rate.

The results of these depth-dependent and depth-integrated analyses are presented in terms of three reworking descriptors: (1) volumetric reworking rate (cm^3/d), (2) D_b (cm^2/d), and (3) α ($(\text{cm}^3/\text{yr})/\text{cm}^3$ or yr^{-1}). Volumetric reworking was calculated from one of the two methods described above and was converted to D_b for comparison with literature values by the relationship:

$$D_b = \frac{\alpha \cdot L_b^2}{2} \dots\dots\dots(4),$$

where α is volumetric reworking in units of inverse time:

$$\alpha = \frac{\text{volumetric reworking rate (cm}^3/\text{yr)}}{\text{volume of image segment (cm}^3)} \dots\dots\dots(5),$$

and L_b is the depth of the bioturbated zone as suggested by Bentley and Sheremet (2003). The “volume of image segment” in the depth-integrated study was the volume of the cropped image (the total volume that the animals occupied); in the depth-dependent portion of the study, it was the volume of an image slice. So, values of D_b and α are depth-integrated in the depth-integrated discussion and depth-dependent in the depth-dependent discussion.

Additionally, compaction analysis was conducted by converting the thickness (in pixels) of discrete sediment layers as bounded by surrounding sands to the thickness in cm using a conversion factor of 81.45 pixels/cm.

C. Results

a. Compaction and Bioturbation Depth

No significant consolidation of bottom layers was observed in any microcosms and no significant change in control microcosms. However, between the time of colonization and the end of the experiment, small populations caused mild (0.2-0.5 cm) dilation in middle sediments (between sand layers 2 and 4), medium-sized populations caused moderate (0.5-1cm) dilation over the top 10cm (between sand layers 1 and 2), and large populations caused mild dilation of top 5cm only (Table 4).

These findings indicate that population density of *H. Elongata* and *Ophiophragmus spp.* is inversely proportional to maximum bioturbation depth (Figure 4). The x-radiographs in Figure 4 illustrate the observation that, along with a limited depth penetration, organisms in higher density populations tended to have increased mobility. For example, the two brittle stars in microcosm 1 created their burrows within 24 hours of their introduction to the system and spent the duration of the experiment simply maintaining and widening a main burrow. On the other hand, the seven brittle stars in microcosm 6 did not create deep or distinct burrows at any time but continually relocated during the 16-week study period. Figure 4 shows that the less populated microcosms contained evidence of sediment penetration ~1.5 times that of the highly populated microcosms.

Table 4: Compaction data. Negative numbers indicate dilation of the sediments and values below 0.2 were attributed to error in measurements.

microcosm	Δh_{LHS} bottom layer	Δh_{RHS} bottom layer	$\Delta h_{\text{LHS total}}$	$\Delta h_{\text{RHS total}}$	Δh_{LHS} top layer	Δh_{RHS} top layer
1	0.20	0.03	-0.28	-0.52	0.00	-0.08
2	-0.01	0.11	-0.42	-0.35	0.05	0.12
3	0.19	-0.04	-1.01	0.09	-0.64	0.28
4	0.16	-0.71	-1.08	-0.50	-0.44	-0.27
5	0.00	-0.06	-0.46	-0.46	0.35	-0.23
6	0.17	0.00	-0.12	-0.58	0.23	-0.17
7	0.05	0.10	-0.44	-0.14	-0.05	0.08
8	-0.05	-0.92	-0.04	0.13	-0.04	0.07

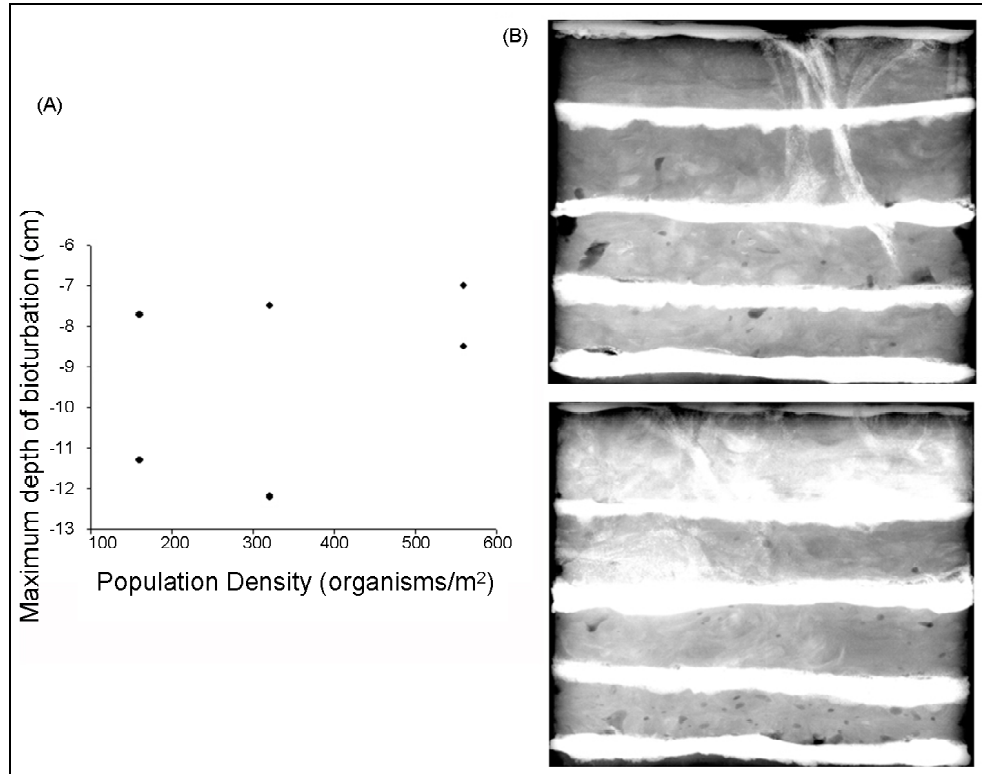


Figure 4 (A) Cumulative bioturbation depth maxima for three population densities of burrowing brittle stars. (B) X-rays equalized and brightened to reveal internal structure of sediment after 10 weeks. Top image is of low-density population in microcosm 1, which primarily maintains old, deep burrow. Bottom images depicts densely populated microcosm 6, in which the maximum depth of bioturbation is much shallower and relocation from one burrow to another occurred more frequently.

b. Depth-integrated Bioturbation

Volumetric bioturbation rates (cm^3/d) derived from burrow outlines are shown in Figure 5. Through the course of the experiment, maximum bulk bioturbation ranged from 4-9 cm^3/d in high, 5-6 cm^3/d in medium, and 4-10 cm^3/d in low density populations. These correspond to average D_b values of 41, 22, and 60 cm^2/d , respectively. Overall time-averaged values of α for each population density were 0.95 yr^{-1} , 0.34 yr^{-1} , and 0.71 yr^{-1} , for low, medium, and high density populations, respectively. Bioturbation rates dramatically decreased at all population densities within 60 days of introduction to the freshly deposited sedimentary fabric. Thus, with

respect to ophiuroid bioturbation, these results suggest that steady state would ensue within two months of re-colonization of an area of seafloor that was previously disturbed by event sedimentation. Steady state volumetric rates fluctuate in the range $\sim 1\text{--}3 \text{ cm}^3/\text{d}$ for all population sizes.

Figure 6 shows a running average of volumetric reworking rate through time, with microcosms of the same population density treated together. The depth-integrated data show a modal distribution with time, such that a maximum reworking rate was reached at 40 days in all population densities. The shape of this curve can be described as occurring in two phases. Phase I may describe the first 40 days and Phase II may describe the time afterwards. In most simplistic terms, Phase I then describes a phenomenon that causes the biological reworking rate to increase and Phase II describes a phenomenon that causes it to decrease.

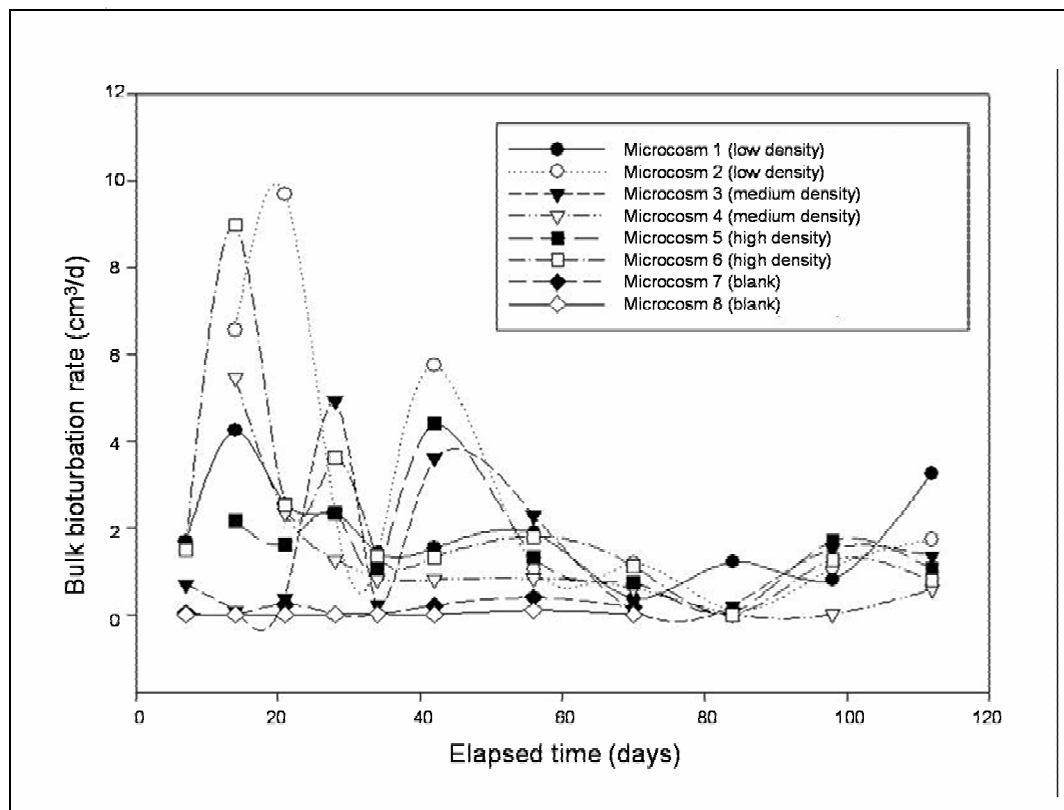


Figure 5: Volumetric reworking in laboratory microcosms.

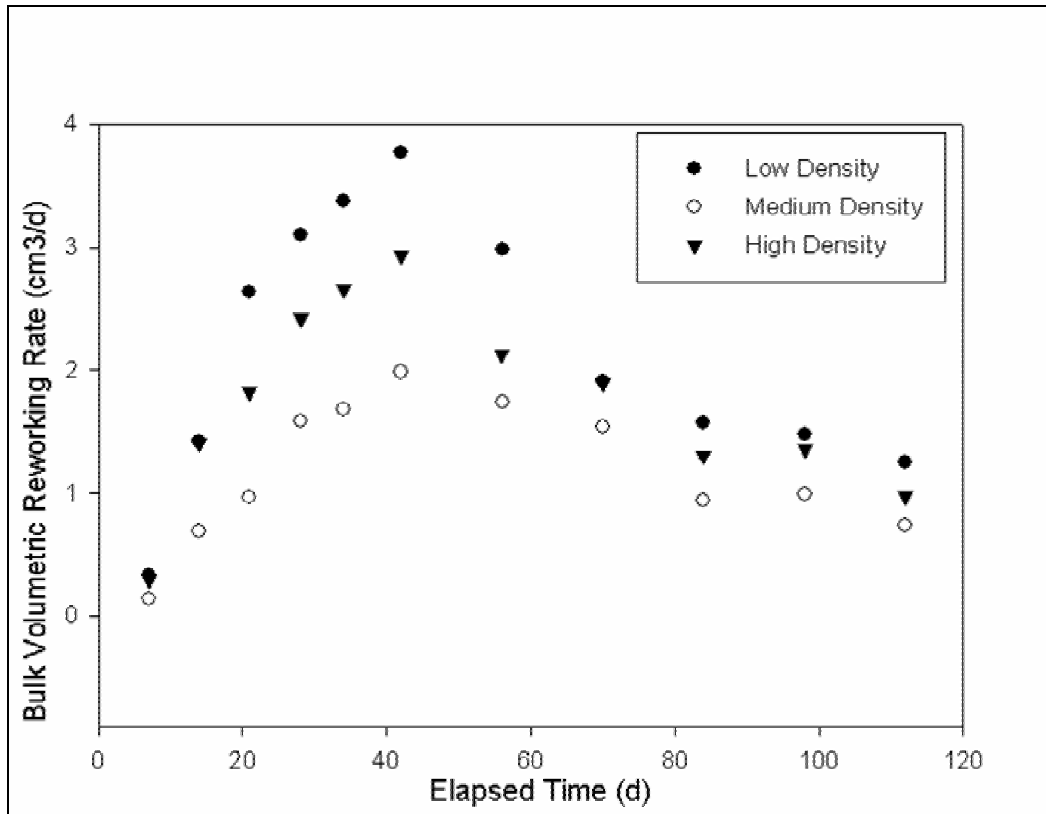


Figure 6: Five-point running average of reworking rates through time

c. Depth-dependent Bioturbation

The variations in surface bioturbation rate are, in part, dependent upon how thick the definition of a “surface” layer is in bioturbation modeling. Here, we assume that the surface can be defined as the top slice of each cropped microcosm, which equates to the top ~2-4 mm of the sediment column. A sampling of “down-core” bioturbation rate profiles is shown in Figure 7.

Volumetric reworking rates were found here to be approximately 0.3-0.4 cm³/d for low and medium densities and ~1-2 cm³/d for low densities at the surface and declined exponentially to the range of ~0.0001-0.02cm³/d for all densities at the base of the mixed layer. These basal reworking rates correspond to D_b values of ~0.001-0.003 cm²/d, which were derived as described above. Each profile’s volumetric reworking rates were converted to α by dividing the reworking rate in each slice by the total volume in each slice (cm). From exponential fits of α with depth,

values fall from $\sim 0.13\text{--}1.2 \text{ yr}^{-1}$ at the surface into the range of $\sim 0.0006\text{--}0.001 \text{ yr}^{-1}$ towards the base of the mixed zone.

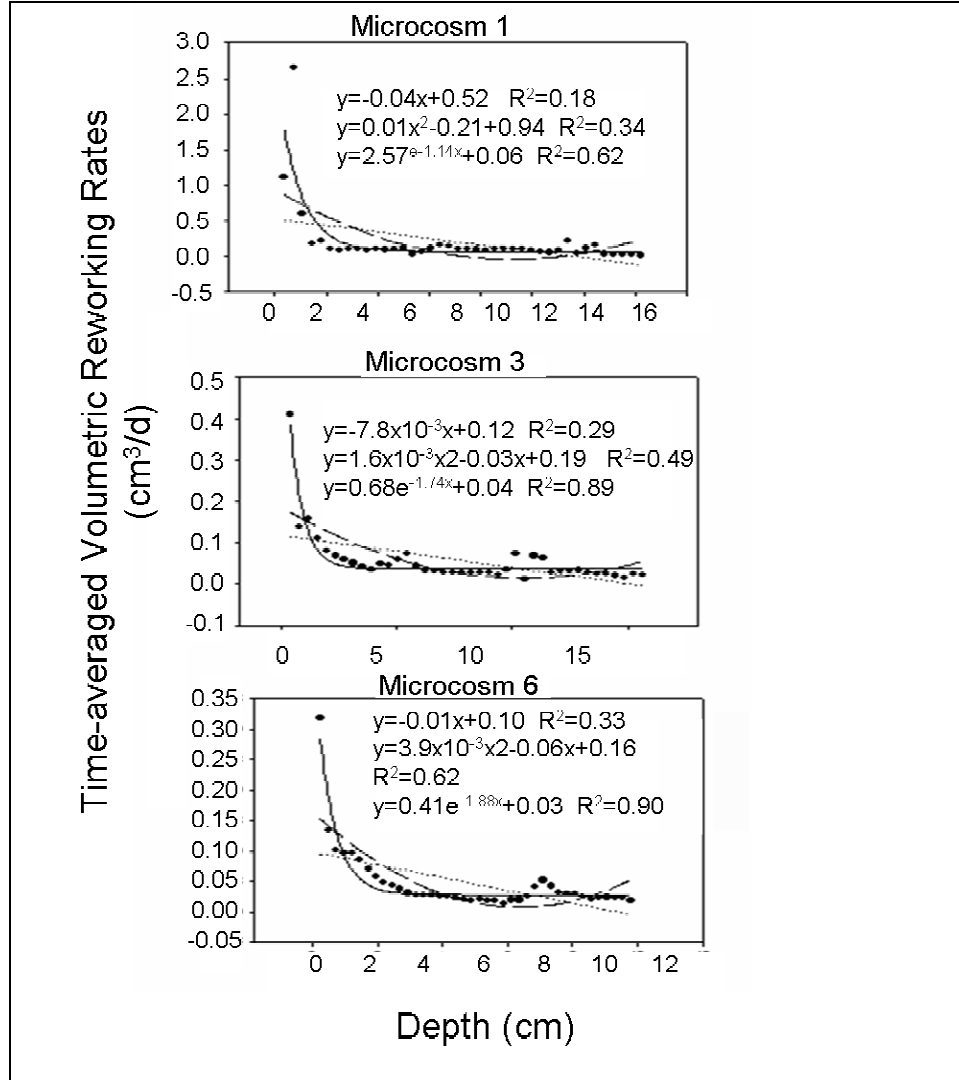


Figure 7: A selection of depth profiles of the volumetric reworking rate averaged through time. In all cases, an exponential curve fits the data best, based on standard regression R^2 values. Solid lines represent exponential fits (3rd eq.), dashed lines represent parabolic fits (2nd eq.), and dotted lines represent linear fits (1st eq.).

The overall evolution of the microcosm sedimentary fabric is summarized in Figure 8, which shows the volume of reworked primary fabric in each microcosm at discrete depth

intervals through time. Most mud particle displacement by volume is done at the surface and, to the base of the bioturbation zone, these numbers decrease exponentially. Reworking rates at depth were about 0.001 those at the surface.

D. Discussion

These results indicate that time-series digital x-radiography can provide useful and adequate measures of biological reworking of fine-scaled stratigraphy but that the method of image analysis affects the results. The reworking rates that result from depth-dependent analysis are lower than those from outlining because of the horizontal averaging process which serves to dilute the mixing signal. Further, because burrow geometry is probably primarily funnel-shaped, the dilution effect must increase with depth. However, low p values (<0.0001) for exponential regressions of volumetric displacement rate versus depth are evidence that there is a significant exponential correlation between these values. R^2 values were significantly higher for exponential curve fits of the same data than for linear or parabolic curve fits. Thus, for further modeling purposes, volumetric reworking by these brittle stars should decrease exponentially with depth below the seafloor.

Conservative estimates of steady state reworking by *H. elongata* and *Ophiophragmus* spp. are $\sim 1\text{-}3\text{ cm}^3/\text{d}$, or $D_b \sim 1\text{-}10\text{ cm}^2/\text{d}$ at the surface and $\sim 0.0001\text{-}0.02\text{ cm}^3/\text{d}$, or $\sim 0.001\text{-}0.003\text{ cm}^2/\text{d}$, at the base of the mixed layer. Deep mixing as described by the biodiffusion coefficient was generally ~ 0.001 times that at the surface. This may seem insignificant over the time frame of this experiment but may be quite relevant to the evolution of an event layer over the time scale of decades, during which it may remain in the mixing zone depending on subsequent sedimentation processes (Bentley and Nittrouer 2003; Bentley et al. in press). Over this period, the implications of deep mixing, although not spatially homogeneous, could be profound with respect to preservation of the layer and observed mottling of the preserved stratigraphy.

The degree of organism crowding in the microcosm was found to affect the preservation of the event layers by influencing maximum bioturbation depth, total volumetric reworking rate, and depth-dependent mixing patterns. The relationship is not linear, however (see Figure 4). Non-linear relationships between population density and these parameters may have been related to the size and individual behavior patterns of these highly mobile brittle stars, oxygen or nutrient availabilities, or other environmental or behavioral patterns which were not evaluated here.

Independent of population density, overall mixing intensity decreased over time to a steady state rate of $\sim 1\text{-}2\text{ cm}^3/\text{d}$ after approximately 60 days from introduction to fresh sediment. However, by tracing the surface layers through time in Figure 8, no such decrease in volumetric displacement of mud particles is evident in any microcosm. Thus, limitations at depth, such as availability of oxygen, nutrients, or space, which affect deep mixing may control overall reworking rates.

A modal distribution of reworking rate with time, described by a phase of increasing bioturbation rate followed by a phase of decreasing bioturbation rate, further suggests a control on the amount of mixing that can take place in a given area of seafloor. There exist several other possible explanations for the modal distribution shown in Figure 6. First, it may be suggested that the modal distribution is a reflection of the methodology, such that Phase II would reflect an inability to detect change within a burrow that may already be well mixed by 40 days after introduction to the sediment. This is unlikely to be the case, however, since the self-obscuring nature of burrowing is more evident in the low density populations than in the high density populations, in which new burrowing occurred for the length of the experiment. Accordingly, one would expect the shape of the curves for low and high density populations in Figure 6 to be significantly different if the cause of the Phase II decrease was methodological. Second, Phase I

may be attributed to a startup period, during which the organisms may have worked rapidly to create their homes and then decelerated once the task was completed. However, it is unlikely that 40 days is the appropriate time to allocate to this startup period since organisms were observed to construct permanent burrows within one day of introduction to the sediment. Accordingly, these results suggest that the reworking rate of a population of these burrowing brittle stars is controlled by two competing processes, one which serves to increase reworking rate and another which serves to decrease it. For example, such competing processes may be related to the bimodal feeding style of the organisms studied here, such that Phase I would represent a time during which organic particulates from natural algal production in the water column was insufficient and so the organisms mostly fed on surface deposits and Phase II would represent a time during which filter feeding rather than deposit feeding dominated, thus creating the appearance of less active sediment mixing.

Observations of an inverse relationship between population and mixing depth are supported by consolidation observations shown in Table 3. Animals in low densities seemed to pump water primarily into the base of the mixed layer, those in medium densities dilated the entire mixed layer, and animals in densely populated areas dilated mainly the upper few cm.

It must be stressed that these results present a picture only of that volume that the animal occupied during the 16-week experimental period and thus cannot account for additional lateral movement that likely occurs in natural settings. Additionally, depth-dependent analyses may not capture lateral mixing as well as vertical mixing but probably provide a good picture of mixing relationships occurring at depth below the seafloor.

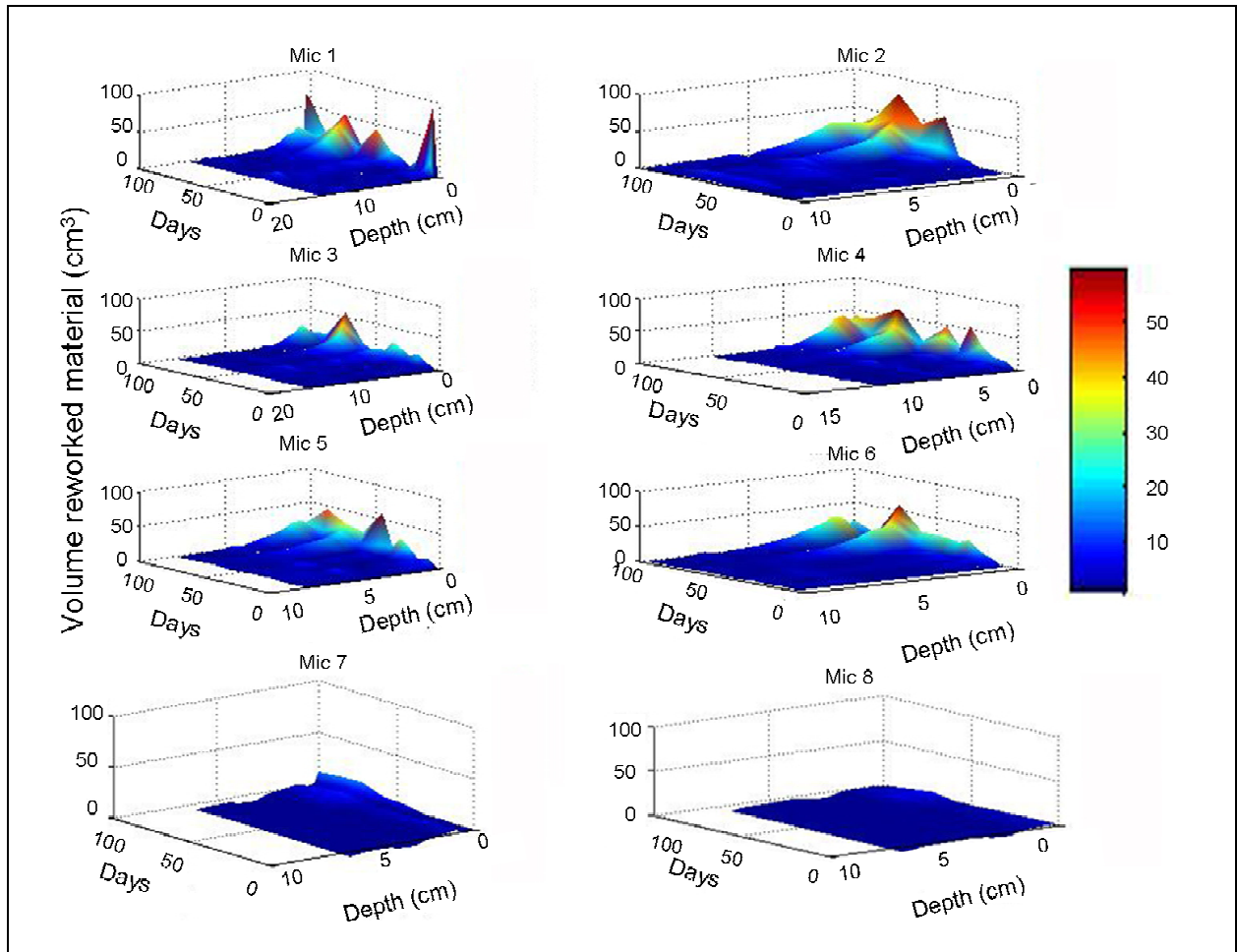


Figure 8: Volume of reworked material in each microcosm through depth and time. Vertical axis is in units of cm^3 of displaced material.

FIELD AND MODELING ANALYSES

A. Hurricane Ivan

An ideal opportunity for the study of bioturbation and event layers presented itself in the guise of Hurricane Ivan in the Mississippi Sound, Mississippi in the autumn of 2004. Hurricane Ivan first made landfall in the US on September 16th, 2004 at Pine Beach, Alabama, 9 miles WSW of Gulf Shores, AL. At that time, it was rated as a category 3 hurricane, with sustained wind speeds of 54 m/s. Peak gusts measured at Pass Christian, Mississippi on September the 16th reached 32.9 m/s, and sustained winds at Waveland, MS were 17.5 m/s with a storm surge of 0.98 m (Stewart 2004). Data on the local effects of the storm were retrieved from the CSI13 WAVCIS data buoy (located at 30.27 N 89.02 W) and show that in the days leading up to Ivan's landfall, significant wave height reached 1.5 m, sustained wind speeds reached 19.6 m/s, and gusts reached 24.2 m/s in the 2-6 m water (NDBC 2004). Unfortunately, data beyond 23:00 on September 15 are unavailable because the station was damaged during the storm.

B. Field and Laboratory Methods

The *R/V Tom McIlwain*, formerly of the University of Southern Mississippi's Gulf Coast Marine Laboratory, embarked from Biloxi, MS on October 4, 2004, 19 days after the Hurricane Ivan's landfall. Thirteen box cores were taken at seven stations previously found to host abundant brittle stars (see Figure 1). Some box cores were sub-sampled for x-radiography, grain size, porosity, and radiochemical analysis. These are shown in a series of figures in Appendix 1. X-radiograph samples were obtained by inserting three-sided Plexiglas trays with sharp bottom edges vertically into the box core and sliding the fourth side on to minimize frictional effects that may cause fabric distortion. The x-ray slabs were sealed with neoprene plugs and stored in a cold room until they were imaged within the subsequent 4 days using the x-ray unit and flat panel digital detector described previously.

The radiotracer used to characterize the event layer was ^{210}Pb ($t_{1/2}=22.3$ yrs), which allows for description of sedimentary evolution over the time period of ~ 100 years.. Sub-samples for radiochemical analysis were obtained by inserting a 10cm diameter PVC core tube into the box core, capping the top and bottom, and then removing the subsample from the corer. These samples were extruded from the PVC tubes aboard the ship at 1 and 2 cm intervals, sealed in plastic bags and kept chilled to retain moisture. In the lab, chosen intervals were weighed, dried, weighed again, and ground before they were sealed with hot glue in 5cm diameter Petri dishes. Porosity was determined by change in mass during drying. Supported ^{226}Ra and ^{210}Pb were allowed to approach secular equilibrium for at least 10 days prior to analysis. The activities of the radiotracers were determined by counting decays for 24 hours on a Canberra planar-style, low-energy intrinsic germanium detector.

Total ^{210}Pb was detected by direct counting at the 46.5 keV peak. Supported ^{210}Pb was estimated by averaging the net counts of intermediate daughter products between ^{222}Rn and ^{210}Pb (^{214}Pb : $t_{1/2}=26.8\text{min}$ with peaks at 295.2 and 352 keV and ^{214}Bi : $t_{1/2}=19.7\text{min}$ with a peak at 609 keV) that were assumed to be in secular equilibrium with ^{210}Pb following ingrowth. This was then subtracted from the total ^{210}Pb to yield excess ^{210}Pb , which was used as a long-term tracer of mixing and sedimentation. Following the methods of Cutshall et al (1983), self-absorption of ^{210}Pb was corrected in each sample using a high-activity sealed standard.

C. Modeling Methods

A previously published (Bentley and Sheremet 2003) bioturbation model has been applied to synthesize laboratory and field findings and extend the time-scale of their utility for future, predictive and hind-casting studies. These authors presented a depth-dependent model that describes bioturbation in terms of a volumetric rate of reworking, α , which is in units of

time⁻¹. In our laboratory study, this is essentially the volume fraction of material reworked at a particular depth by an animal or community of animals (Eq. 4).

The degree to which bioturbation has reworked sediment is described by a unitless preservation quotient, q , which represents the percentage of original fabric in place at a given point on a time-depth trajectory, such that physical fabric as it is laid down has a $q=1$. As the physical fabric gets destroyed by biological reworking, the q value decreases but may not be lower than 0. The bioturbation rate is considered to be depth-dependent, such that $\alpha = \alpha_0 \exp(-\beta z)$, where z is depth, α_0 is the volumetric bioturbation parameter at the sediment-water interface and β is a constant that describes the exponential decrease in α with depth. Values of α and β were based on exponential fits of the $\alpha(z)$ vs. depth at selected times for each microcosm (Table 6). To simulate event deposition, the frequency and intensity of events in this model may be specified by the user and a maximum bioturbation depth, L_b (units of length), indicates the maximum vertical extent of biological reworking. In our model evaluations, these parameters were taken from field measurements in the Mississippi Sound and laboratory results, respectively.

D. Field Results

Sand to mud ratios, radiochemical profiles, and digital x-radiographs taken from cores at LSU-1, which is located just north of Horn Island, (Figure 1) in October, 2004 and June, 2005 are shown in Figure 9. During both sampling trips, a thick mud layer associated with Hurricane Ivan penetrated the sediment column to approximately 11cm. Very few biogenic traces were present at either sampling time. Mottled sandy sediments below ~15cm are more typical of ambient pre-storm sediments. ²¹⁰Pb profiles show a well-mixed layer from the surface to 11 cm in both cores. Porosity data are shown in Figure 10 and display a signal of normal though moderate consolidation of the storm-generated mud layer. During the summer sampling trip, the

polychaete *Parandalia americana* was relatively abundant, with no evidence of the key bioturbators normally inhabiting this location.

Five additional box cores were subsampled during the October 2004 sampling trip, the locations of which are marked on the map in Figure 1. Sand to mud ratios combined with radiochemistry data and digital x-radiography for all of these cores reveal that the event layer produced in the Mississippi Sound and the shelf beyond its barrier island boundary ranged from 4-11 cm. X-radiograph, radiochemistry, and grain size data from these cores are illustrated in Appendix 1.

Table 6: averages through time of all α values using 3 parameter exponential curve fitting. P values for all values of α_0 and β were <0.0001

microcosm	α_0 (yr ⁻¹)	β (cm ⁻¹)	L_b (cm)	R^2
1	1.2	1.1	11	0.62
2	0.13	2.1	7.7	0.86
3	0.14	1.7	12	0.89
4	0.20	2.2	7.5	0.90
5	0.13	2.1	7	0.86
6	0.14	1.9	8.5	0.90

E. Modeling Output

Figure 11 shows the output from the Bentley and Sheremet (2003) model for conditions in which a single depositional event, producing a layer 11cm thick like that at LSU-1, occurred at the beginning of an 8 month model run. The α_0 and β values were taken from Table 6, which was derived from exponential curve fits to time-averaged $\alpha(z)$ with depth data. Additionally, the model has been used to project what we might see in the MS Sound if the event layer from Hurricane Ivan was overlain by a ~15cm thick layer from the passage of Hurricane Katrina and no further events occurred for 15 years. These results are shown in Figure 12.

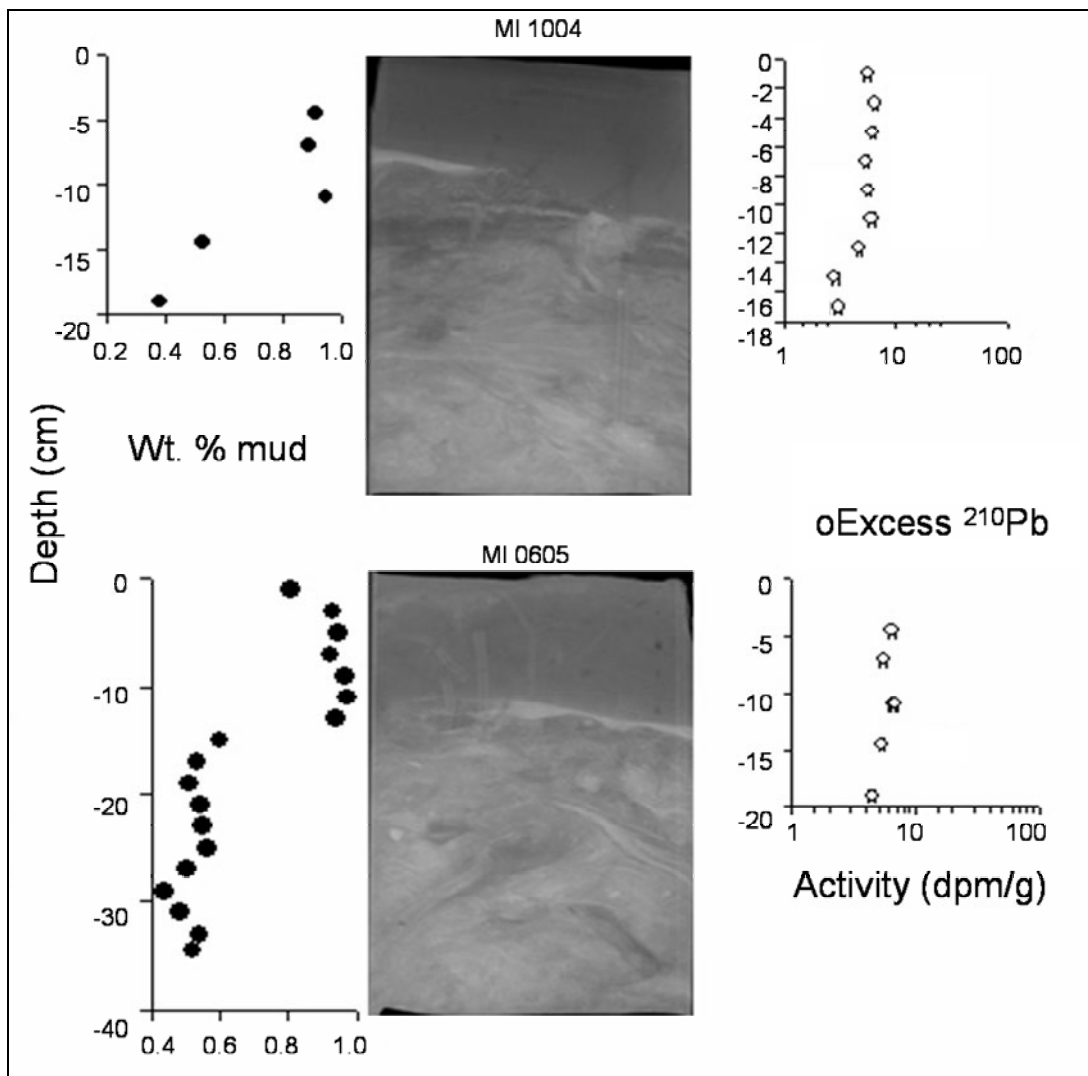


Figure 9: Grain size (left), x-radiography, and radiochemical profiles for two box cores taken at LSU-1. The top panel contains data taken in the fall trip and the bottom panel contains data from 8 months after the event, in June.

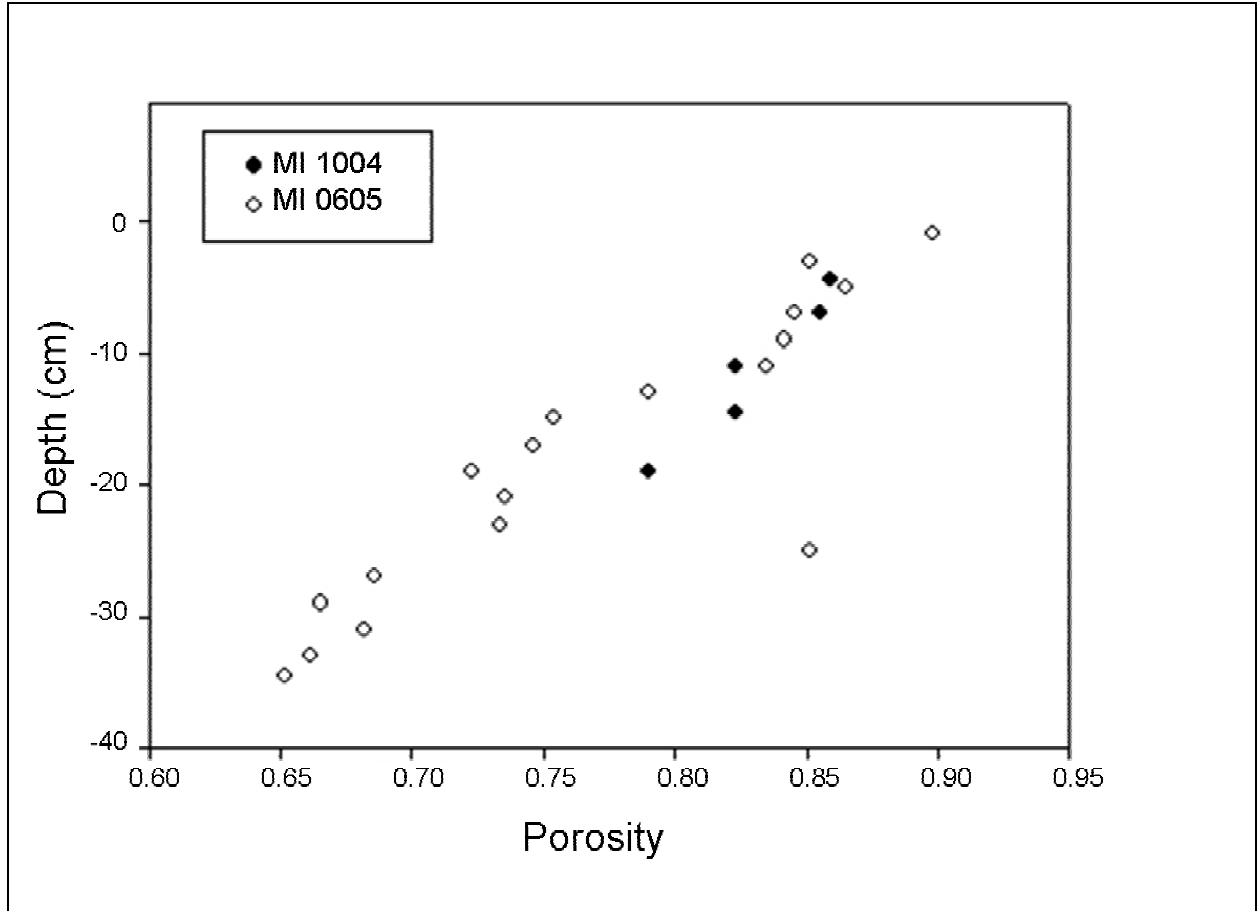


Figure 10: Porosity data from two box cores from LSU-1

The value of q was calculated independently of the model using pixel intensities from microcosm x-radiographs directly. Using the cropping and slicing method described above, an integrated q projection for each microcosm was obtained by subtracting the pixel intensity at a particular depth and time from in the initial, unpopulated microcosm:

$$q_{z,t} = \frac{I_{pix_{z,t}} - I_{pix_{z,t_0}}}{I_{pix_{z,t}}} \dots\dots\dots(6).$$

Pixel intensity rather than volume calculations were used to describe overall change in the tracer distribution because the volumetric measurements actually refer to volumes of sand or water in mud, it is possible to have >100% change, which creates q values that are not within the range $0 < q < 1$. The results of this analysis are shown in Figure 13.

F. Discussion of Field Results and Model Output

Previous surveys (see table, Appendix 1) have indicated that a relatively constant and stable community of brittle stars occupies the sampling stations visited for this study. However, an unexpected finding during the June 2005 sampling trip was that, sediment deposited by Hurricane Ivan in the Mississippi Sound was not re-colonized by the local population of brittle stars during the 8 month interim period. Rather, small polychaete *P. americana* were found. In light of this, 8 months after the storm, little evidence for reworking of the stratigraphy that would have been predicted using laboratory experiments and modeling techniques was found (Fig. 11). Sand to mud ratios showed distinctive muddy sediments associated with the event, which was underlain by fining upward sequences of sandy mud. Traces in x-radiographs are attributed to *P. americana* rather than the burrowing brittle stars used for the laboratory study. Thus, there exists evidence of a lag time associated with repopulation by key bioturbators which may be at least 8 months. The event layer was traced laterally to the shelf beyond the estuary and had thicknesses ranging from 2-11 cm, which generally thickened in a seaward transect.

Calculations of q show that most of “event layer” destruction in the microcosms was not apparent until about 70 days after introduction. Most of reworking occurred in the upper 8-10 mm, but some reworking is apparent down to L_b . Ideally, model and field data from 8 months after Hurricane Ivan’s landfall could be compared. However, since field results were not indicative of any significant reworking at that point, this research can only suggest that Figure 11 shows the evolution of the event layer as it would have been seen if brittle stars had re-colonized the area more quickly. Based on model output seen in Figure 12, any sedimentary fabric (physical or biogenic) developed up to one year after the original mixing event would likely be well preserved because of its probable burial beneath an event layer created by Hurricane Katrina in September, 2005. Future studies of event strength and frequency with respect to layer

preservation may exploit this situation in the Mississippi Sound to investigate the soundness of these predictions.

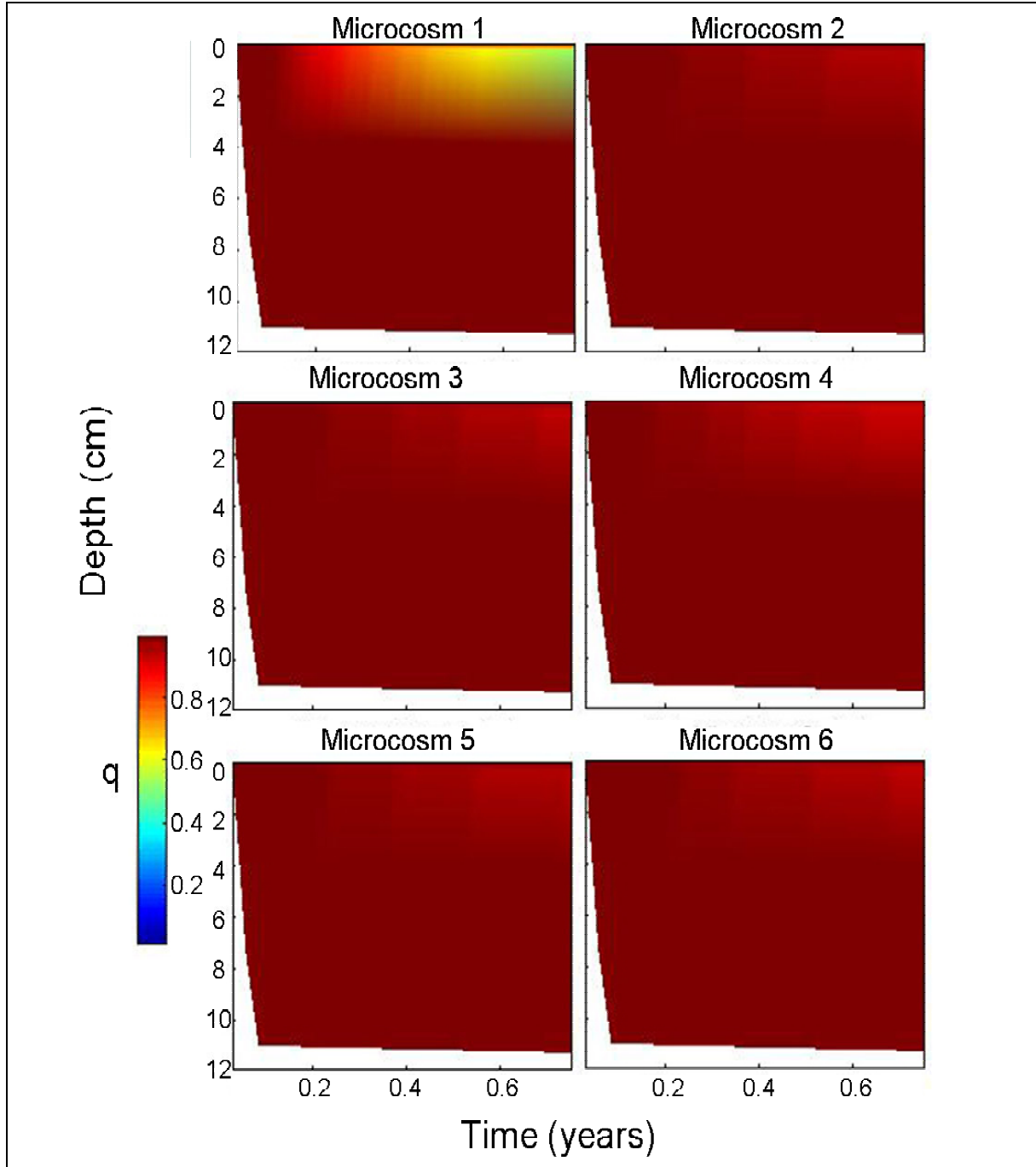


Figure 11: Fractional preservation, q , calculated from the model presented by Bentley and Sheremet (2003) using parameters from each microcosm for an 8 month run. Values of α and β were extracted from exponential curves of α (averaged through time) vs. depth.

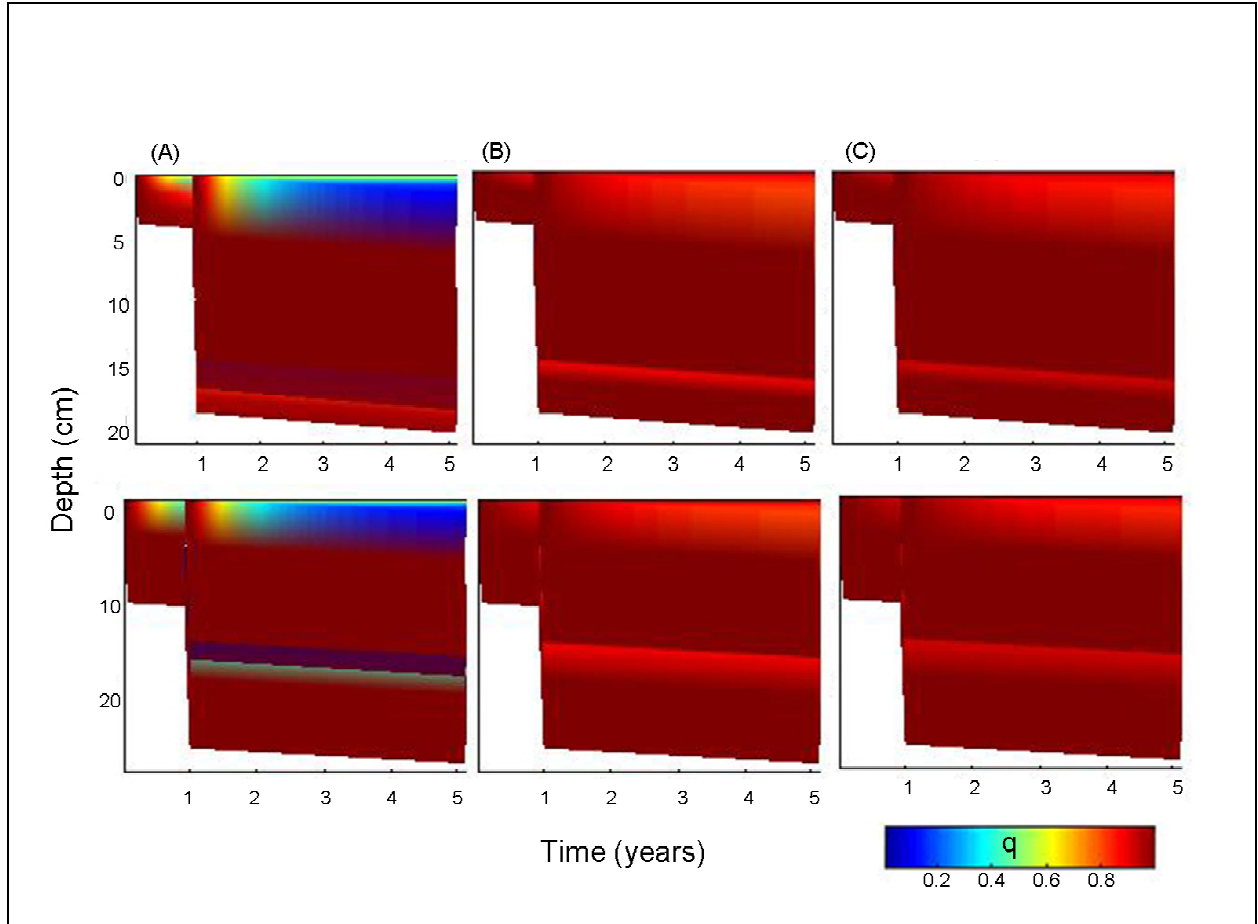


Figure 12: Fractional preservation, q , for a 5 year model run using values of α_0 and β from time-averaged curves from low-microcosm 1 (A), medium-microcosm 4 (B), and high-microcosm 6 (C) density microcosms. Top images show evolution of portions of the event layer that were 4 cm deep while bottom images show the same evolution of the 11 cm portions of the layer. A 15 cm event at month 11 represents estimates of a second layer from Hurricane Katrina in August of 2005.

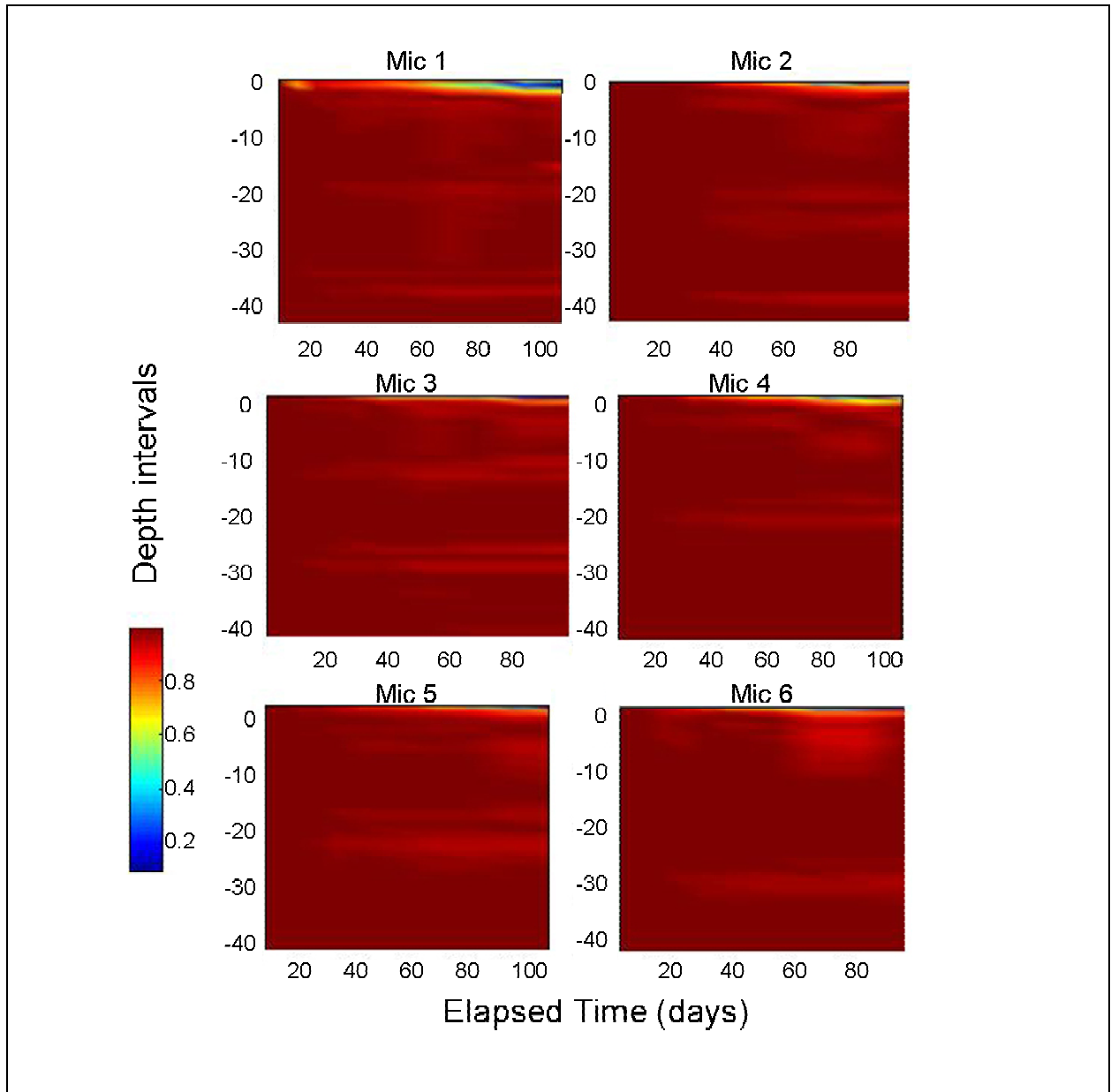


Figure 13: Values of q calculated from pixel intensity changes in laboratory microcosm experiments.

SUMMARY AND CONCLUSIONS

Through the study of brittle star reworking of event sedimentation in laboratory experiments, field surveys, and modeling applications, the following conclusions have been reached. First, digital time-series x-radiography of laboratory microcosms provides usable data about particulate displacement through time. However, of the two image analysis methods used to extract and analyze these data, one approach yields higher bioturbation rates than the other. Ophiuroids *H. elongata* and *Ophiophragmus spp.* reached steady state reworking rates within 60 days of introduction to fresh sediment and these depth-independent rates ranged from 1-3cm³/d, independent of population density. In depth-dependent analyses, reworking was found to occur at the surface at a rate of about 1-2cm³/d and declined exponentially with depth to about 0.001 the surface rates at the base of the mixed layer. Mixing occurred more deeply in low population densities in laboratory experiments. The results of this research indicate that population density plays an expected role in the kind of bioturbation modeling that is appropriate for use over time scales of several months.

A muddy event layer was produced in the Mississippi Sound, Mississippi near the time of Hurricane Ivan's landfall. This event layer ranged from 2-11cm in thickness and is measurable in x-radiographs of box cores both 19 days and 8 months after the storm traversed the estuary. The layer reached a maximum thickness around and just beyond the southern boundary of the estuary, with very little evidence of reworking between sampling events. No key bioturbators were found in the federally protected coring location just north of Horn Island; rather, *P. americana* were present during the second sampling.

A model created by Bentley and Sheremet (2003) can be parameterized using measurements made from these lab and field studies and may yield useful predictions on event preservation in light of further episodic sedimentation.

REFERENCES

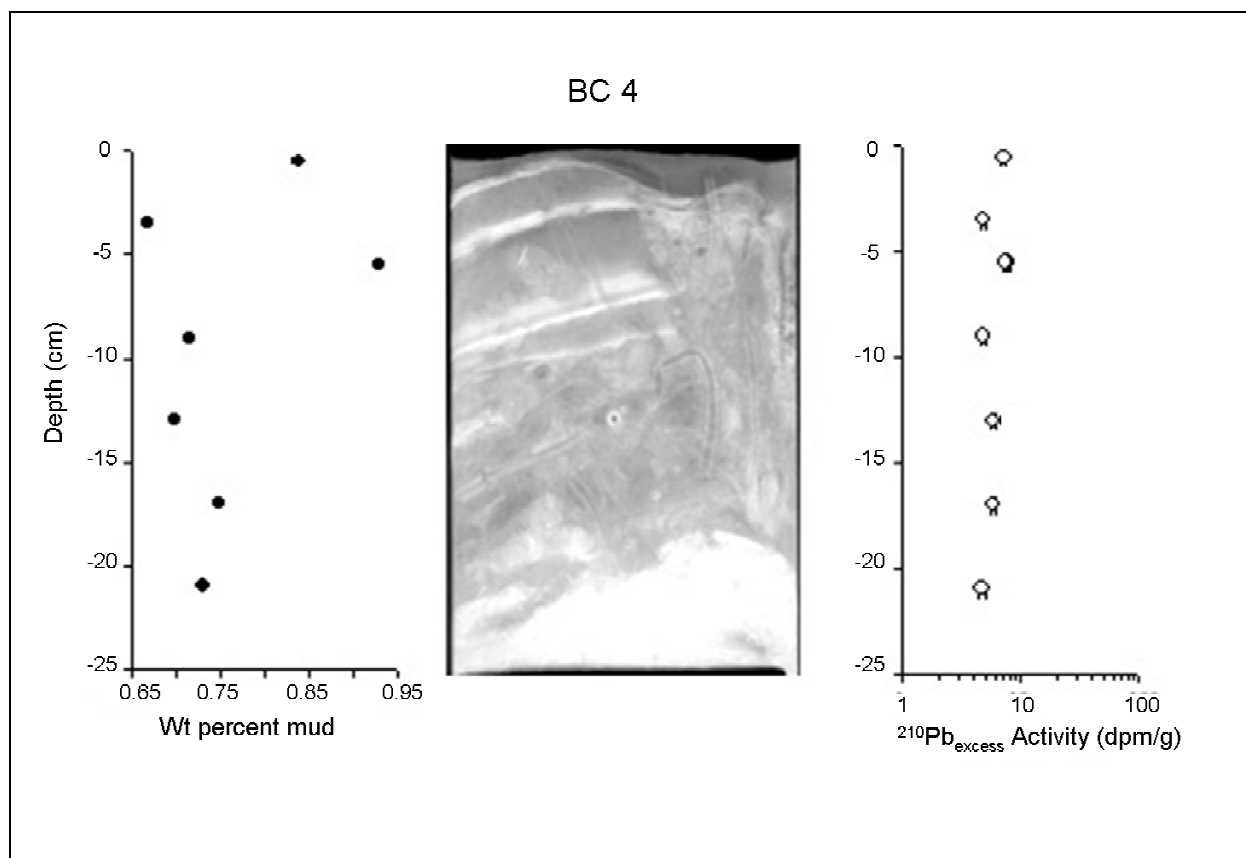
- Bentley, S.J., Furukawa, Y. Vaughan, W.C. 2000. Record of event sedimentation in the Mississippi Sound. *Transactions of the Gulf Coast Association of Geological Societies*. 50: 617-625.
- Bentley, S.J., Keen, T.R., Blain, C.A., Vaughan, W.C. 2002. *Marine Geology*. 186: 423-446.
- Bentley, S.J. and Nittrouer, C.A. 2003. Emplacement, modification, and preservation of event strata on a flood-dominated continental shelf: Eel shelf, Northern California. *Continental Shelf Research*. 23(16): 1465-1493.
- Bentley, S.J. and Sheremet, A. 2003. New model for the emplacement, bioturbation, and preservation of fine-scaled sedimentary strata. *Geology*. 31: 725-728.
- Bentley, S.J., Sheremet, A., Jaeger, J.M. In press, 2006. Event sedimentation, bioturbation, and preserved sedimentary fabric: Field and model comparisons in three contrasting marine settings. *Continental Shelf Research*.
- Berner, R.A. 1980. Early Diagenesis: A Theoretical Approach. Princeton, NJ, Princeton University Press
- Boudreau, B.P. 1986(a). Mathematics of tracer mixing in sediments: I. Spatially-dependent, diffusive mixing. *American Journal of Science*. 286: 161-198.
- Boudreau, B.P. 1986(b). Mathematics of tracer mixing in sediments: II. Nonlocal mixing and biological conveyor-belt phenomena. *American Journal of Science*. 286: 199-238.
- Boudreau, B.P., Choi, J., Meysman, F., Francois-Carcaillet, F. 2001. Diffusion in a lattice-automaton model of bioturbation by small deposit feeders. *Journal of Marine Research*. 59(5): 749-768.
- Bryant, E.A., Young, R.W., Price, D.M. 1992. Evidence of tsunami sedimentation on the southeastern coast of Australia. *Journal of Geology*. 100(6): 753-765.
- Christensen, A.B., and Colacino, J.M. 2000. Respiration in the burrowing brittlestar, *Hemipholis elongata* Say (Echinodermata, Ophiuroidea): a study of the effects of environmental variables on oxygen uptake. *Comparative Biochemistry and Physiology Part A* 127: 201-213.
- Cutshall, N.H., Larsen, I.L., Olsen, C.R. 1983. Direct analysis of ^{210}Pb in sediment samples: self absorption corrections. *Nuclear Instruments and Methods*. 206:1-20.
- Darwin, C. 1896 The formation of vegetable mould through the action of worms, with observations on their habits. New York, D. Appleton & co.

- Dott, R.H. and Bourgeois, J. 1982. Hummocky cross-stratification—significance of its variable bedding sequences. *Geological Society of America Bulletin* 93(8): 663-680.
- Frey, R.W. ed. 1975. The Study of Trace Fossils: A synthesis of principles, problems, and procedures in ichnology. New York: Springer-Verlag. 562 pages.
- Furukawa, Y., Bentley, S.J., Lavoie, D.L. 2001. Bioirrigation modeling in experimental benthic microcosms. *Journal of Marine Research*. 59(3): 417-452.
- “Islands.” (January 6, 2003) National Parks Service—Gulf Islands National Seashore—Mississippi District. Retrieved March 10, 2006.
<http://www.nps.gov/guis/extended/MIS/MNature/Islands.htm>
- Keen, T.R., Bentley, S.J., Vaughan, W.C., Blain, C.A. 2004. The generation and preservation of multiple hurricane beds in the northern Gulf of Mexico. *Marine Geology*. 210: 79-105.
- Kneller, B.C. and Branney, M.J. 1995. Sustained high-density currents and the deposition of thick massive sands. *Sedimentology*. 42(4): 607-616.
- Ludwick, J.C. 1964. Sediments in the Northeastern Gulf of Mexico. In: Miller, R.L., ed., Papers in Marine Geology: Shepard Commemorative Volume. New York: MacMillan. p. 204-240.
- Moore, D.G., and Scruton, P.C. 1957. Minor Internal Structures of Some Recent Unconsolidated Sediments, *Bulletin of the American Association of Petroleum Geologists*. 41(12): 2723-2751.
- NDBC. 2004. Station SIPM6-Ship Island Pass, MS/CSI13, NOAA. 2005.
- NOAA. (2005, November 29, 2005). “NOAA reviews record-setting 2005 Atlantic hurricane season: Active hurricane era likely to continue.” Retrieved December 2, 2005, from <http://www.nhc.noaa.gov/2005atlan.shtml>.
- NOAA. (2004, November 29, 2005). “2004 Atlantic Hurricane Season.” Retrieved December 2, 2005, from <http://www.nhc.noaa.gov/2004atlan.shtml>.
- Reese, E.S. 1966. The complex behavior of echinoderms. In: Boolootian, R.A., ed. Physiology of Echinodermata. New York: Interscience Publishers. p. 157-218.
- Rhoads, D.C. and Boyer, L.F. 1982. The effects of marine benthos on physical properties of sediments: A successional perspective. In: McCall P.L., and Tevesz, M.J.S. Animal-Sediment Relations. New York: Plenum Press. p. 3-52.
- Rice, D.L. 1986. Early diagenesis in bioadvective sediments: Relationships between the diagenesis of beryllium-7, sediment reworking rates, and the abundance of conveyor-belt deposit-feeders. *Journal of Marine Research*. 44: 149-184

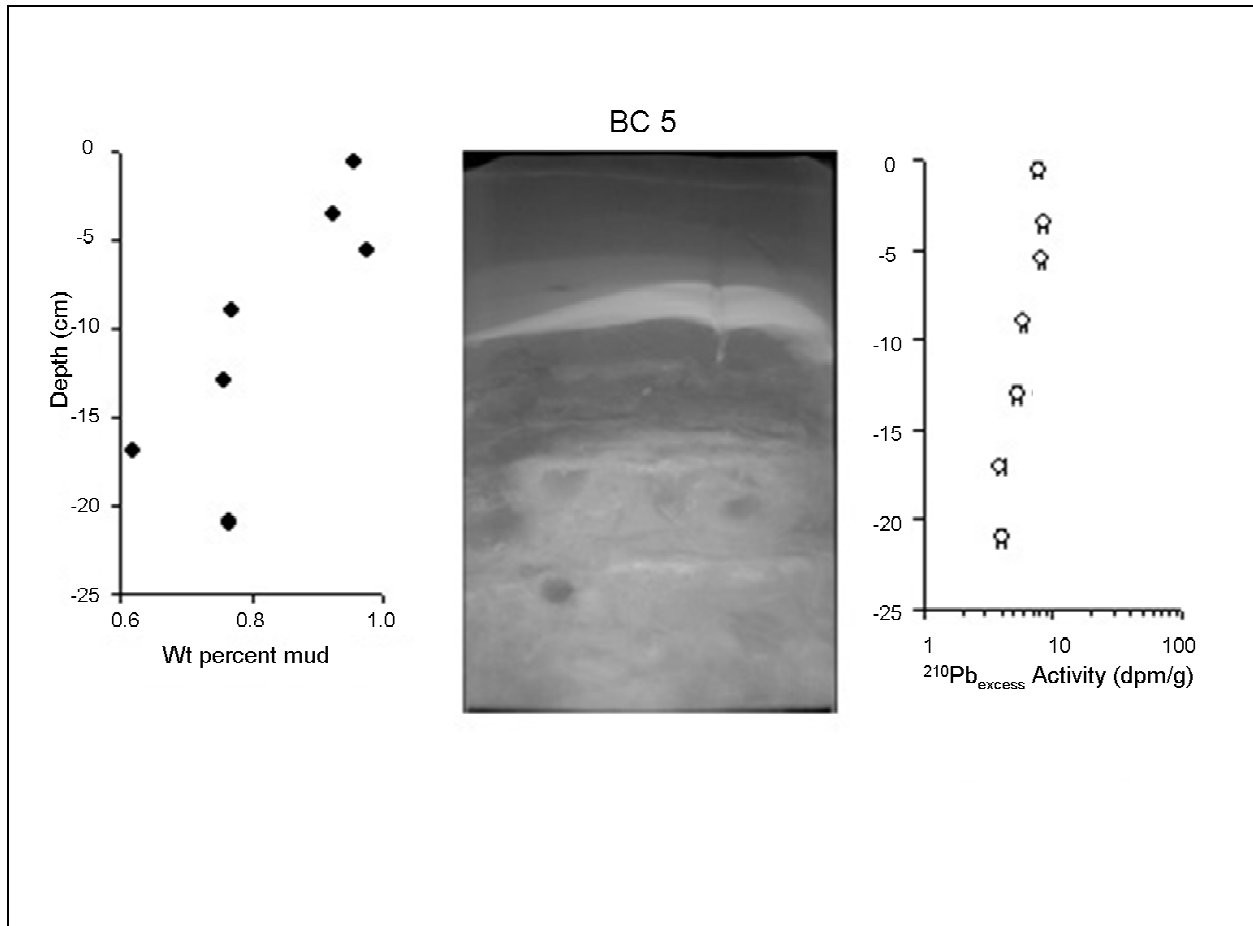
- Richter, R. 1952. Sediment-Gaseinien und Sedifluktion uberhaupt: Notizbl. *Hess. L.-Amt. Bodenforsch* 3: 67-81.
- Stewart, S.R. (2004, June 3, 2005). "Hurricane Ivan." Tropical Cyclone Report. Retrieved November 17, 2005, from <http://www.nhc.noaa.gov/2004ivan.shtml?>
- USEPA. 1999. Ecological condition of estuaries in the Gulf of Mexico. EPA 620-R-98-004. U.S. Environmental Protection Agency, Office of Research and Development, National Health and Environmental Effects Research Laboratory, Gulf Ecology Division, Gulf Breeze, Florida. 80 pp.
- Valentine, J.F. 1991. Temporal variation in populations of the brittle stars *Hemipholis elongata* (Say, 1825) and *Microphiopholis atra* (Stimpson, 1852) (Echinodermata: ophiuroidea) in eastern Mississippi Sound. *Bulletin of Marine Science*. 48(3): 597-605.
- Velardo, B.M., Bentley, S.J., Stone, G.W. 2003. Impacts of tropical storms on sedimentary fabric of the Mississippi Sound. *Transactions of the Gulf Coast Association of Geological Societies*. 53: 816-823.
- Velardo, B.M. 2004. Detailed geochronology of the Mississippi Sound during the late Holocene. Unpublished masters thesis, Louisiana State University, Baton Rouge, Louisiana.

APPENDIX: FIELD SURVEY DATA

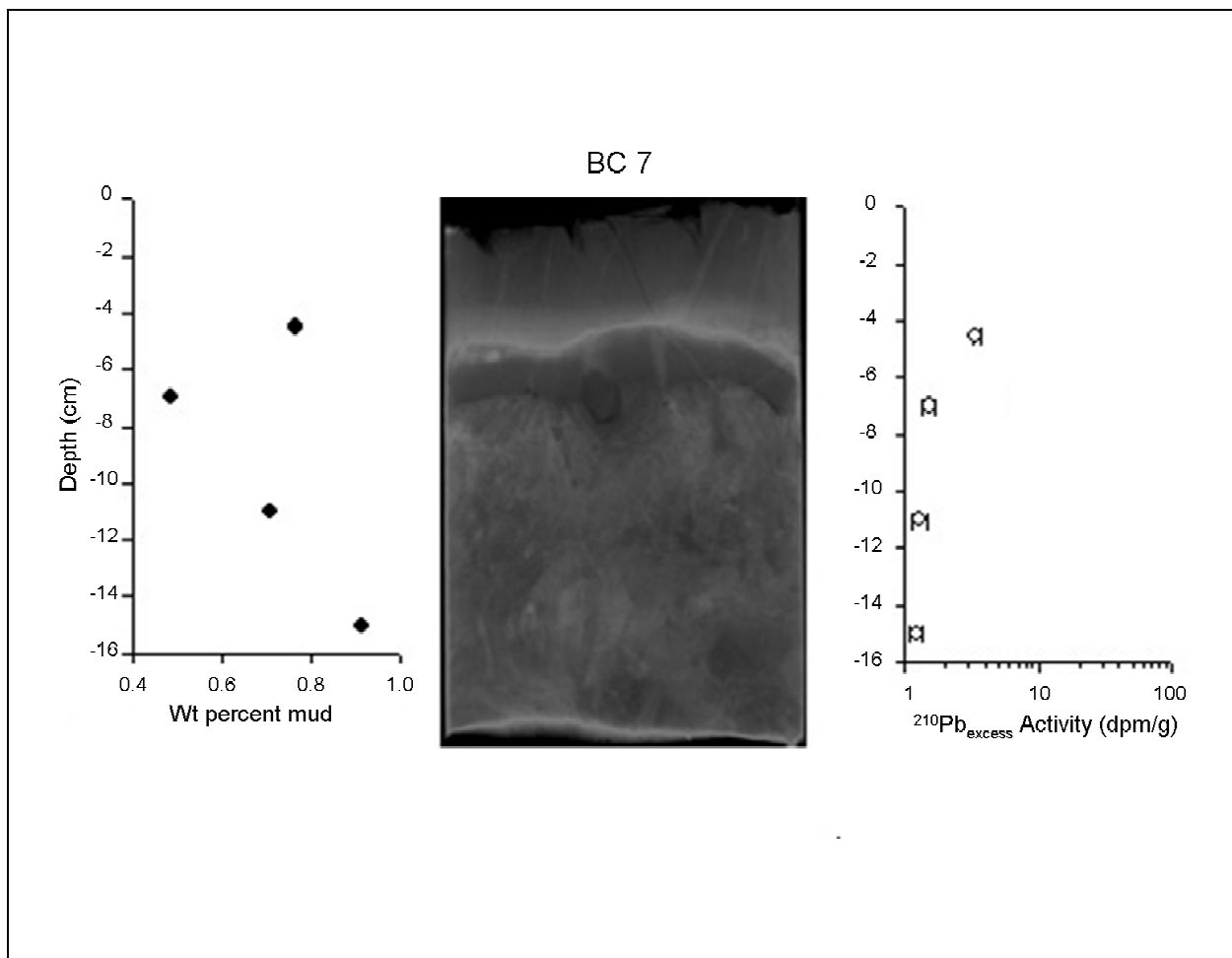
Date	Lat deg	Lat min	Long deg	Long min	BR. STARS	SM BR STARS	H. ELONGATA	M. ATRA	O. MOOREI	SCHIZO	CAPITELLIDS	BIVALVES	PARANDALIA	ECHINURANS	TUBIC POLY
07/06/00	30	15.99	88	48.04											
07/06/00	30	14.98	88	48.02											
07/06/00	30	15.21	88	48.08											
07/06/00	30	15.48	88	47.97											
07/06/00	30	15.76	88	48.02											
07/06/00	30	15.74	88	51.50											
07/06/00	30	15.45	88	51.66											
07/06/00	30	11.52	88	50.28											
02/10/99	30	16.00	88	46.00			63	4	12						
05/18/99	30	16.93	89	18.72						19					
05/18/99	30	16.00	89	21.00						7					
05/18/99	30	14.00	89	20.00						79					
05/18/99	30	13.00	89	18.00						74					
05/19/99	30	21.00	88	54.00			31			1	5				
05/19/99	30	17.00	88	56.00	51										
05/19/99	30	13.25	88	58.50		68						7			
05/19/99	30	16.00	88	52.00		10						15			
05/19/99	30	16.00	88	46.00		15	43				4	6			
07/08/99	30	14.00	89	20.00	3					54	3		4		
07/09/99	30	16.00	88	45.20	6	6					6	1			
07/09/99	30	16.10	88	45.85	8	4					84				
07/09/99	30	16.00	88	46.00	30	9						5		17	17
11/17/99	30	16.00	88	46.00	5	6					3				
11/17/99	30	16.00	88	46.00	19	12					MANY				
11/17/99	30	16.10	88	45.85											
12/9/99	30	14.00	89	20.00	8					5					
12/9/99	30	14.00	89	20.00	5					11					
12/9/99	30	14.00	89	20.00	10					21					
12/9/99	30	14.00	89	20.00	9					28					
12/9/99	30	14.00	89	20.00	13					20					
12/9/99	30	14.00	89	20.00	21					23					
12/9/99	30	14.00	89	20.00	8					16					
04/05/00	30	15.33	88	46.00			72	1				6			
04/05/00	30	16.00	88	40.00	6	9					5				
04/05/00	30	16.00	88	43.00	3						3	11			
04/05/00	30	16.00	88	43.00	9						2	7			
04/05/00	30	16.25	88	45.65	8						7	4			
04/05/00	30	16.00	88	48.00	18						1	5			
04/12/00	30	14.00	89	20.00	28					27					
04/12/00	30	14.00	89	20.00	20					14					
04/12/00	30	14.00	89	20.00	10					15					
04/12/00	30	14.00	89	20.00	14					19					
04/12/00	30	14.00	89	20.00	12					25					
04/12/00	30	14.00	89	20.00	32					32					
04/12/00	30	14.00	89	20.00	35					45					



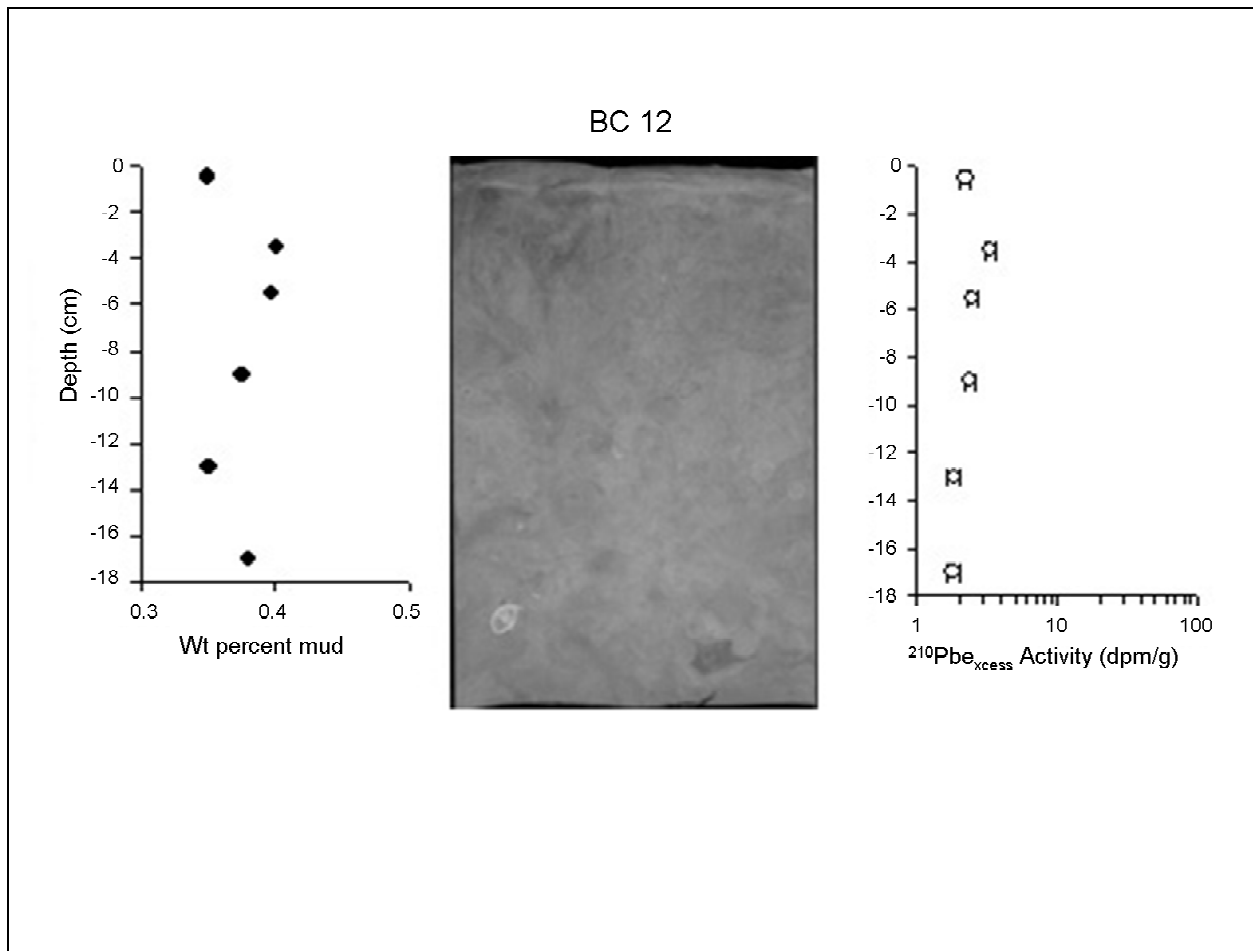
In BC4, taken at LSU-2, remnants of old events are visible in the upper left side of the x-ray slab. The layers may be tilted on account of the box core entering the seafloor at an angle. A very noticeable feature of this sample is the evidence of heterogeneity in over small length scales within a region. Here, the right hand side of the x-ray is nearly thoroughly mottled down to a depth of approximately 20cm, with burrow tubes suggesting that the reworking has been caused by burrowing infauna.



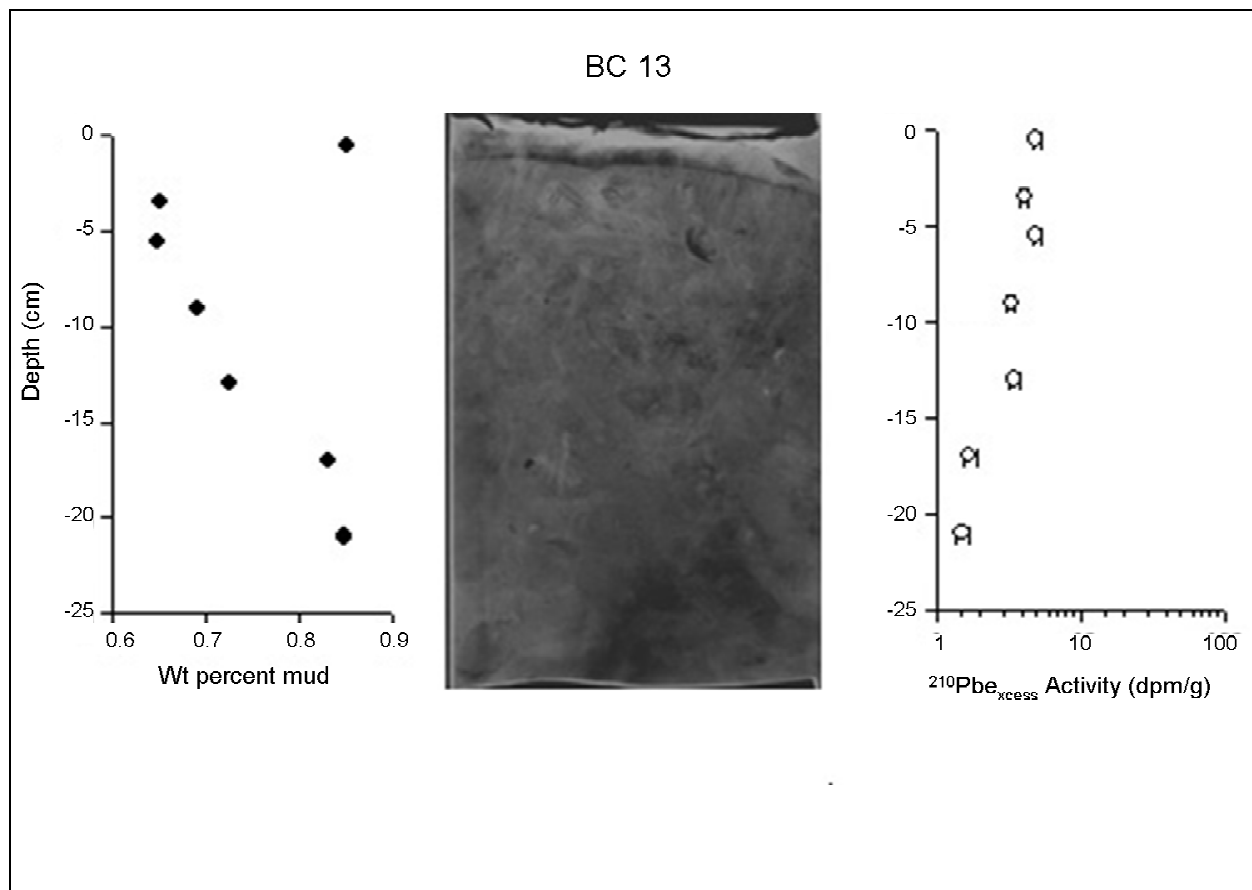
BC5, taken at LSU-3 shows a sand wedge at the base of an event layer that extends down to about 8cm.



BC7 was taken at LSU-4. Here is a wedge of sand at about 6cm, very mottled mud below it, and some reworked mud above it.



BC12, taken at LSU-6 displays little evidence of a storm layer. The top ~25cm of the sediment column appears to be homogenized by burrowing infauna and the mottling is difficult to distinguish from the unmottled top ~2 cm, which probably represents Hurricane Ivan.



BC 13 was taken at LSU-7. Grain size analyses indicate a slightly sandy mud lens at about 5 cm, above which is the muddy top of the event layer.

VITA

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