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Research Article

Sediment Chemistry and Meiofauna from the Northern Gulf of Mexico Continental Shelf

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This study examined sediment chemistry, granulometry, and meiofauna on the northern Gulf of Mexico continental shelf from central Louisiana to Apalachicola, Florida. Sediment samples were collected in October/November 2012 with a Shipek grab sampler from 26 locations (extending from 28°18′46.079″N, 91°10′44.471″W to 29°3′48.383″N, 85°28′25.679″W) at depths ranging from 49 to 361 m. Sediment analysis revealed two distinct profiles to the east and west of the Mississippi River Delta at approximately 88°30′W. The concentrations of silt + clay, organic carbon, Ba, Cr, Cu, Fe, Ni, Pb, V, and Zn were higher in western sites and positively correlated with Al concentrations. Eastern sites contained sandier sediments with lower organic carbon concentrations and higher Sr and Ca concentrations. Nematode densities were higher at western sites and positively correlated with Al, Cr, Cu, Fe, Ni, Pb, Zn, silt + clay, and organic carbon concentrations. Copepod densities correlated with very coarse + coarse sand, exhibiting higher densities at eastern sites. PAH concentrations were relatively low, with all sites having <1700 μg/kg total PAHs. This study has revealed two distinct sediment profiles in the eastern and western zones of the study, which appear to influence the nematode and copepod densities.

1. Introduction

The Gulf of Mexico (GOM) Deepwater Horizon Oil Spill (DHOS) of 2010 was the largest oil spill in the United States' history, releasing 4.6 million barrels of oil (731 million liters) [1]. Heavy oiling occurred on the coastal areas of Louisiana to Florida, while deep-sea sediments may have been affected by the oil on the sea floor [1–3]. More recently (July 2013) another smaller event, the Hercules-256 natural gas platform blowout, occurred less than 100 kilometers from the coast of Louisiana [4]. In March of 2014, approximately 4,000 barrels (635,949 liters) of additional oil were released into Galveston Bay [5].

In light of recent and ongoing accidents involving human activities in the GOM, there is a growing need for the documentation of the overall condition of this ecosystem. Efforts to catalog the health of US coastal ecosystems began around the 1960s [2] and many recent studies have focused on deep-sea benthic communities [1, 6, 7]. However, few studies have examined the benthos of the GOM continental shelf, though this habitat contains microscopic communities (meiofauna) that serve as the base of an immense food chain. These meiofauna are important benthic components that are often used as indicators in pollution studies [8].

This study examines continental shelf sediment chemistry and general meiofauna trends near the 100 m isobath in the northern GOM. This research expands on a preliminary report by Landers et al. [9], by examining meiofauna and sediment relationships over a broad area of the northern GOM continental shelf.

2. Methods

2.1. Sample Collection. Sediment samples were collected using a Shipek grab sampler aboard the National Oceanic and Atmospheric Administration (NOAA) ship *Gordon*

Gunter along the northern GOM continental shelf and slope in October and November of 2012 (Figure 1). Sample depths ranged from 49 to 361 m (mean = 120 m). One hundred and thirty sediment samples were obtained from 26 sites (three for meiofauna analysis and two for sediment analysis per site) (Table 1). Sediment grabs were collected to a 10.2 cm depth (bite depth of Shipek grab sampler) and then subcored three times to a 5 cm depth with a coring tube (15.19 cm^2 area). These nested subcores targeted the subsurface meiofauna, since the Shipek grab disturbs the fine flocculent surface of the sediment. The three subcores were preserved in 5% formalin (final concentration) for meiofauna analysis. Two additional samples were taken from the remaining sediment in the Shipek grab for PAH, trace metal, organic carbon, and granulometric analysis. Global Positioning System coordinates, water temperature, depth, salinity, and dissolved oxygen were recorded by NOAA at each site. Figure 1 was created in ArcGIS 10.2.2. The ocean basemap was downloaded from http://www.arcgis.com/home/item.html?id=9a12467d1d574a9c836607821fd7fe04 on September 10, 2014. The basemap was compiled by Environmental Systems Research Institute and other contributors. Bathymetry data were also obtained on September 10, 2014, from the United States Geological Survey's Coastal and Marine Geology Program at http://www.arcgis.com/home/item.html?id=9a12467d1d574a9c836607821fd7fe04.

2.2. Meiofauna Analysis. Sediment samples were sieved in the laboratory with a 333 μm presieve, followed by 63 and 45 μm sieves. Ludox centrifugation was used to extract the meiofauna from the sediment [10, 11]. Meiofauna were then stained with rose bengal, counted, and identified to major group under a stereomicroscope at Troy University according to Higgins and Thiel [12]. Though the 45 and 63 μm samples were counted separately to allow for comparisons with past studies that used one of the two sieves, the data were combined in order to report density values representing total meiofauna larger than 45 μm.

2.3. PAH Analysis. Sediment PAHs were determined at Troy University using Soxhlet extraction with dimeth-ylene chloride following EPA method 3540C [13]. PAH concentrations were analyzed using a Shimadzu GC/MS (GC-2010-mass spectrometer) calibrated for petroleum hydrocarbon analysis. The precision of the instrument was ±1%. Each sample was divided into three subsamples consisting of two replicates and a spiked subsample. Certified reference standards were purchased from Absolute Standards, Inc. for 27 PAH calibrations. Each sample was analyzed for the following 27 PAHs (16 EPA priority PAHs in italics): *naphthalene*, 2-methylnaphthalene, 1-methylnaphthalene, biphenyl, 2,6-dimethylnaphthalene, *acenaphthylene, acenaphthene,* dibenzofuran, 2,3,5-trimethylnaphthalene, *fluorene,* dibenzothiophene, *phenanthrene, anthracene*, carbazole, 1-methylphenanthrene, *fluoranthene, pyrene, chrysene, benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene,* benzo(e)pyrene, *benzo(a)pyrene*, perylene, *dibenzo(a,h)anthracene, benzo(g,h,i)perylene,* and *indeno(1,2,3-cd) pyrene*.

Table 1: Latitude, longitude, and grab depth at each sampling site.

Site	Latitude (°N)	Longitude (°W)	Depth (m)
73	28°18′46.079″	91°10′44.471″	65.2
75	28°7′28.488″	90°53′37.319″	113.2
77	28°22′7.499″	90°30′44.064″	49.3
78	28°11′34.943″	90°18′55.368″	128.1
80	28°49′22.764″	89°42′38.627″	69.7
81	28°47′0.671″	89°33′40.392″	87.5
82	28°37′59.340″	89°13′16.319″	242.0
83	28°46′27.191″	89°4′30.180″	360.8
84	28°58′51.024″	88°59′56.472″	84.8
85	29°7′56.711″	88°42′27.467″	86.1
86	29°17′21.156″	88°33′21.239″	65.7
87	29°21′58.428″	88°28′27.299″	58.8
89	29°24′30.168″	87°51′21.491″	74.4
90	29°28′58.008″	87°27′53.532″	85.3
91	29°38′23.063″	87°24′10.871″	65.3
97	29°56′41.135″	86°55′4.584″	150.9
98	29°55′51.131″	86°31′25.752″	79.8
99	29°45′16.200″	86°22′37.128″	102.3
102	29°41′0.348″	86°22′9.659″	114.1
103	29°32′52.655″	86°16′42.959″	123.8
104	29°31′21.756″	86°6′38.448″	81.3
111	29°19′0.732″	85°44′39.408″	60.9
112	29°3′48.383″	85°28′25.679″	61.5
113	28°48′17.604″	85°47′10.608″	220.8
161	28°35′47.472″	85°46′35.399″	259.4
162	28°44′45.167″	85°52′5.015″	259.2

2.4. Trace Metal and Organic Carbon Analysis. Samples were analyzed for 31 metals and organic carbon content at the Central Analytical Instruments Research Laboratory of Louisiana State University. Metal concentrations were analyzed using an Inductively Coupled Plasma Analyzer (Varian Vista MPX ICP-OES) following EPA method 200.7 [14]. Inductively coupled plasma calibration standards were prepared in the HCl + HNO_3 acid matrix, similar to the sample matrix. Sediment samples were digested at 120°C for 30 minutes using trace metal grade nitric and hydrochloric acids. Instrument calibration was verified using a 2nd source multielement standard purchased from Exaxol Chemical Corporation. The analytical precision of the instrument was ±3%. Percent recovery of metal was determined by spiking the sample with the known amount of concentration. To determine the amount of organic carbon, soil samples were initially treated with dilute HCl to remove inorganic carbonates followed by total carbon determination by dry combustion at 980°C using a TruSpec CN analyzer (LECO, St. Joseph, MI). The CN analyzer was calibrated using NIST soil standards. The precision of the instrument was ±2% and the protocol followed EPA method 9060 [15].

2.5. Granulometric Analysis. Granulometry was determined at Jacksonville State University. Sediment samples were dried

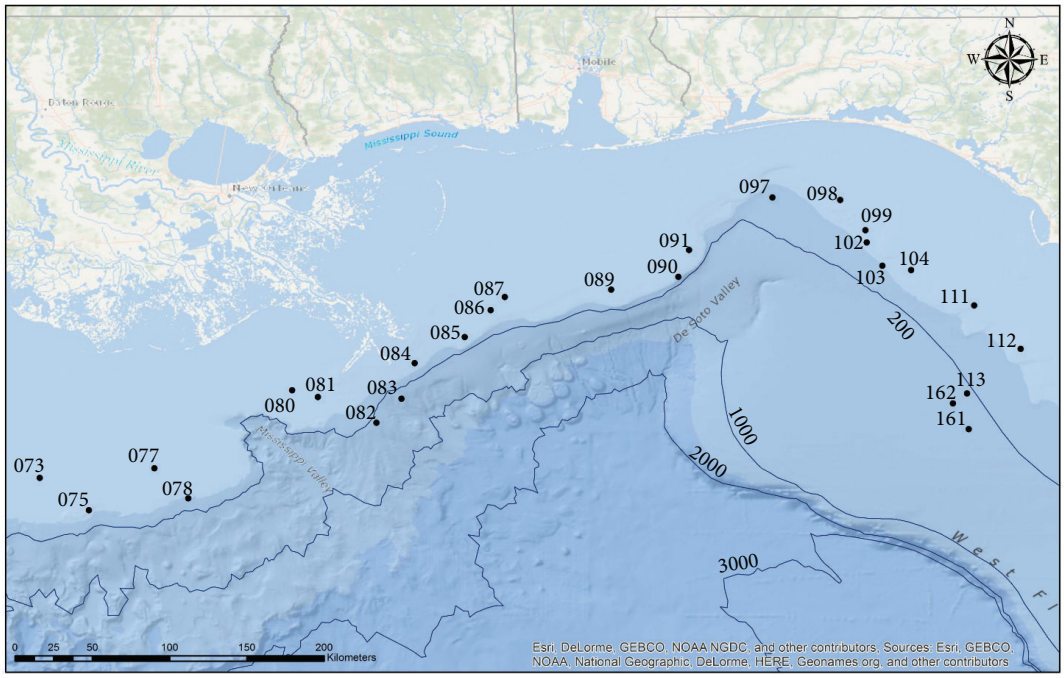

Figure 1: Sample locations in the northern GOM along the continental shelf and slope (contours in meters).

at room temperature, treated with 30% hydrogen peroxide, and heated to 45°C overnight to remove organic material. Dried material was separated using a Geotech Sand Shaker Mechanical Sieve (Geotech Environmental Equipment, Denver, CO) into the following categories: granules (>2 mm), very coarse + coarse sand (2 mm–500 μm), medium sand (500 μm–250 μm), fine sand (250 μm–125 μm), very fine sand (125 μm–63 μm), and silt + clay (<63 μm).

2.6. Data Analysis. Negative longitudinal values were converted to positive values for statistical analysis (i.e., 87°W versus −87°W). Concentrations of trace metals and individual PAHs that were below detection limits were set at zero for graphing and statistical analysis. Nematode and copepod densities at each site were calculated as the mean number of individuals/10 cm^2. Metals were expressed in mg/kg and PAHs in μg/kg, and granulometric characteristics and organic carbon were expressed as a percentage of the total sediment. Data were analyzed using the SPSS 12.0 Spearman's rank correlation.

3. Results

3.1. Sediment Metal Analysis. Analysis of metals focused on Al, Ba, Ca, Cr, Cu, Fe, Ni, Pb, Sr, V, and Zn. This focus was due to the relationship of these metals to oil contamination and drilling and relevance to granulometry [16–20]. The data revealed two metal-related associations in the sediment, one to the west of sites 86/87 (Figures 1–3; Table 1) and one to the east (Figure 4). These two sediment regions differed significantly in the concentrations of Al and Ca, which had

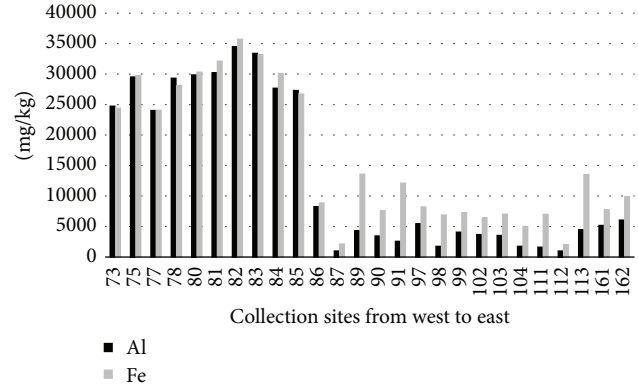

Figure 2: Al and Fe concentrations by site, from west to east along the GOM continental shelf.

markedly different correlations to the other metals (Figures 2, 4; Table 2).

Aluminum concentrations were highest in the western study areas (Figure 2). A sharp decline in Al concentration was found slightly east of the Mississippi River Delta, from 27,315 mg/kg at site 85 to 8,258 mg/kg at site 86. This pattern was also seen with Cr, Cu, Fe, Ni, Pb, V, and Zn, each of which correlated directly with Al and longitude (Figures 2, 3; Table 2). Barium also correlated significantly with Al and longitude and was present in much higher concentrations than most trace metals, reaching 1,124 mg/kg at site 78.

Calcium had a significant negative trend when compared with Al, Ba, Cr, Cu, Fe, Ni, Pb, V, and Zn (Figure 4, Table 2). Concentrations of Ca were much higher in the eastern study sites, ranging from 4,120 mg/kg at site 81 to a peak of

Table 2: Spearman's rank correlations (r) between meiofauna density, granulometric and site characteristics, and trace metal, organic carbon, and PAH concentrations.

	Nem	Cop	N : C	Al	Fe	Ca	Sr	Long	Depth
Al	.541**	−.139	.439*	1.000	.935***	−.695***	−.757***	.733***	.429*
Ba	.368	−.186	.350	.895***	.846***	−.715***	−.782***	.848***	.248
Cr	.522**	−.167	.457*	.892***	.909***	−.657***	−.650***	.687***	.347
Cu	.503**	−.022	.338	.949***	.916***	−.628**	−.682***	.644***	.466*
Fe	.406*	−.119	.366	.935***	1.000	−.656***	−.749***	.744***	.302
Ni	.496**	−.086	.382	.961***	.911***	−.654***	−.704***	.652***	.492*
Pb	.408*	−.085	.331	.869***	.868***	−.821***	−.813***	.793***	.184
V	.370	−.098	.346	.933***	.965***	−.661***	−.721***	.774***	.329
Zn	.505**	−.146	.425*	.986***	.945***	−.669***	−.748***	.703***	.450*
Ca	−.446*	.204	−.432*	−.695***	−.656***	1.000	.932***	−.770***	.134
Sr	−.367	.085	−.269	−.757***	−.749***	.932***	1.000	−.774***	.092
Organic C	.552**	−.237	.503*	.869***	.752***	−.696***	−.657***	.595**	.416*
Silt + clay	.409*	−.060	.298	.724***	.588**	−.624**	−.623**	.535**	.238
Very coarse + coarse sand	−.024	.545**	−.385	.073	.193	.108	.027	.013	.060
EPA PP PAH	−.141	.103	−.331	.210	.053	.045	−.090	.156	.147
Total PAH	−.248	.185	−.457*	−.025	−.124	.220	.102	−.104	.085
Long	.273	−.150	.274	.733***	.744***	−.770***	−.774***	1.000	−.123
Depth	.251	−.137	.328	.429*	.302	.134	.092	−.123	1.000

*Correlation is significant at 0.05 level.
**Correlation is significant at 0.01 level.
***Correlation is significant at 0.001 level.
Nem: nematode density; Cop: copepod density; N : C: ratio of nematodes to copepods; Long: longitude.

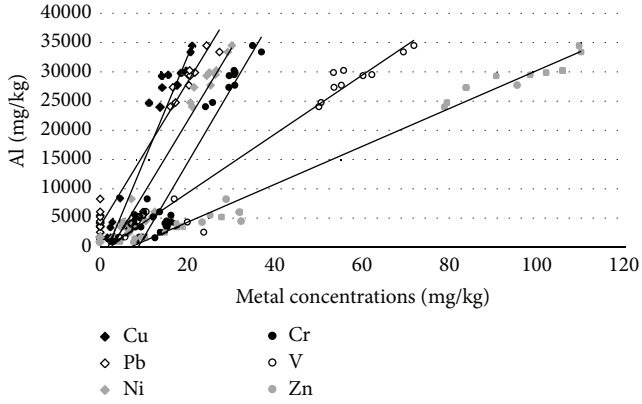

Figure 3: Cu, Pb, Ni, Cr, V, and Zn concentrations graphed as a function of Al concentrations.

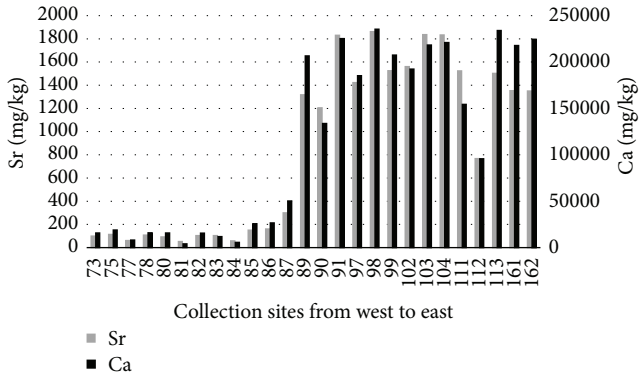

Figure 4: Sr and Ca concentrations by site, from west to east along the GOM continental shelf.

235,362 mg/kg at site 98 (Figure 4). Strontium concentrations were also much higher in the eastern study area, reaching 1,863 mg/kg at site 98, located just northeast of the De Soto Valley. All sites west of sites 86/87 contained strontium concentrations less than 300 mg/kg.

3.2. Sediment PAH Analysis. Total PAH and EPA priority pollutant PAH concentrations were relatively low, ranging from 16 to 1,624 μg/kg (Table 3). Concentrations were not higher in Louisiana than in Florida, despite the proximity of the sites to the DHOS location (28°44′12″N, 88°23′13.8″W) and the extensive oil activities in coastal Louisiana [21]. The values were lowest in central study sites and generally increased in the east and the west (Figure 5). PAHs that were below detection limits at all locations included *naphthalene,* biphenyl, 2,6-dimethylnaphthalene, *benzo(b)fluoranthene, benzo(k)fluoranthene*, and perylene.

3.3. Sediment Granulometry Analysis. Granulometric analysis revealed differences in eastern versus western sites when comparing the silt + clay (<63 μm) fraction with the very fine sand (125 μm–63 μm) fraction of the sediment (Figure 6). The highest silt + clay (Figure 6) and organic carbon percentages (Table 3) were found in western sites and generally decreased in eastern sites, where very fine sandy sediments were more

Table 3: Total PAH, total EPA priority pollutant PAH and organic carbon concentrations, and animal densities at each site.

Site	Total PAH (μg/kg)	Total EPA PP PAH (μg/kg)	Organic carbon (%)	Nematodes/10 cm^2	Copepods/10 cm^2
73	928	704	1.4	58	4
75	1164	630	1.06	206	12
77	1006	565	0.78	162	10
78	815	327	1.01	52	2
80	591	337	1.34	295	9
81	234	177	1.33	245	2
82	141	125	1.09	88	1
83	16	16	1.4	376	5
84	94	94	1.29	792	21
85	144	144	1	132	3
86	159	141	0.5	163	3
87	231	196	0.33	37	3
89	144	75	0.39	86	2
90	109	68	0.43	70	1
91	174	95	0.31	32	49
97	339	183	1.06	193	5
98	256	175	0.3	48	14
99	278	123	0.77	340	8
102	505	335	0.99	109	2
103	619	325	0.83	74	1
104	219	135	0.38	210	21
111	351	110	x	70	2
112	360	119	0.31	54	68
113	1150	562	0.68	60	4
161	886	395	0.79	104	11
162	1624	818	0.83	66	13

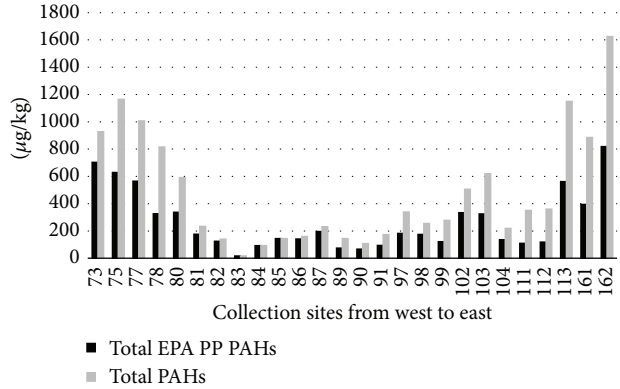

Figure 5: Total concentrations of the 16 EPA priority pollutant PAHs and total PAHs by site, from west to east along the GOM continental shelf.

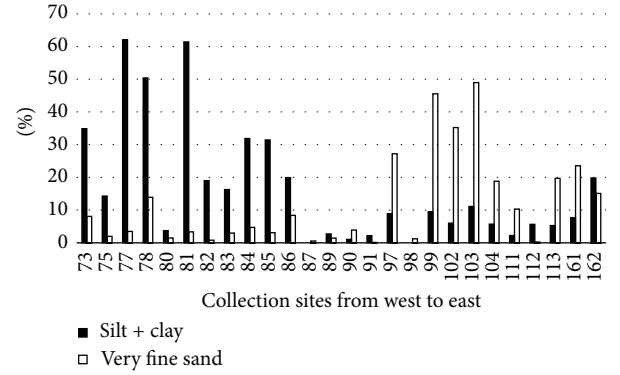

Figure 6: The silt + clay and very fine sand percentages of the sediment by site, from west to east along the GOM continental shelf.

prevalent. The very coarse + coarse sand percentage (relevant to copepod abundance) revealed no clear distribution pattern.

3.4. Meiofauna Density. Nematodes were generally more abundant in the western study sites, with the highest density of 792 nematodes/10 cm^2 at site 84 (Figure 7, Table 3) and a mean density of 159 nematodes/10 cm^2 across all sites. Conversely, the highest copepod (and copepodite) densities were found in eastern locations, with 68 copepods/10 cm^2 at site 112 (Figure 8, Table 3) and a mean density of 11 copepods/10 cm^2 across all sites. The ratio of nematodes to copepods (N : C), which has been used as an indicator in pollution studies [22, 23], was highest at site 81 where

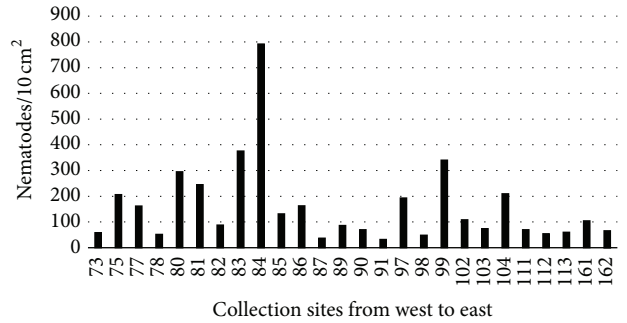

Figure 7: Nematode density by site, from west to east along the GOM continental shelf.

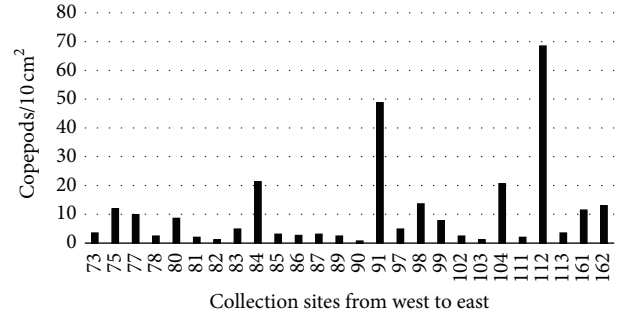

Figure 8: Copepod density by site, from west to east along the GOM continental shelf.

nematode density was over 100 times greater than copepod density (Table 3).

3.5. Statistical Correlations. Spearman's correlations support the trends observed in the raw data in that two distinct sediment zones exist along the continental shelf (Table 2). These two distinct areas can be observed via an analysis of metal type and concentration, granulometry, and meiofauna density.

3.5.1. Sediment Zones. The western area of the study revealed strong positive correlations between Al and Ba, Cr, Cu, Fe, Ni, Pb, V, and Zn, all of which correlated positively with longitude (Figures 2-3, Table 2). Organic carbon (Table 3) and silt + clay percentages (Figure 6) also correlated with longitude and were found in higher percentages in western sites (Table 2). In contrast, sediments from the eastern study area consisted of high concentrations of Sr and Ca (both negatively correlated with longitude) (Figure 4, Table 2) and very fine sand (Figure 6).

3.5.2. Meiofauna. Nematode density positively correlated with concentrations of Al, Cr, Cu, Fe, Ni, Pb, and Zn and silt + clay and organic carbon percentages (Table 2). Nematode density and N : C were both negatively correlated with Ca, while N : C negatively correlated with total PAHs (Table 2). Copepod density correlated positively with very coarse + coarse sandy sediments (Table 2).

4. Discussion

This study documents the sharp contrast in sediment characteristics that exists on the northern GOM continental shelf. The low concentrations of Al east of the Mississippi River Delta and the sharp increase in concentrations near site 86 are likely attributable to the outflow of the Mississippi River, which is rich with terrestrial-derived Al from the weathering of continental rocks [24]. Weathered Al complexes with silicate material and aggregates other trace metals to form aluminosilicate clay minerals [24, 25].

Since trace metals are naturally found in aluminosilicate minerals, Al is often used to normalize their concentrations [20, 25, 26]. In the current study, the correlation of Cr, Cu, Fe, Ni, Pb, V, and Zn with Al (and longitude) suggests that these metal variations are naturally occurring, likely bound with silicate, clayey material derived from the outflow of the Mississippi River and not from anthropogenic input [19, 20, 24]. McGowen et al. [19] found that these metals (with the exception of Zn, which was not measured) were highly present in fluvial sediments and several showed an affinity for fine sediments with high organic carbon content, as found in our study.

Similar to Al, Fe concentrations may be used to normalize trace metals and reveal those concentrations that are attributable to river outflow [20, 27]. Iron concentrations in this study correlated strongly with Al and showed a similar relationship to that of Al with the remaining metals. Barium also correlated with Al in this study, though it is likely elevated due to the high concentration of Ba in drilling muds and the high frequency of drilling operations in the western part of the study area, where Mississippi River-derived aluminosilicate minerals are prevalent [20, 28]. Thus, although elevated Ba correlated with elevated Al in the west, this correlation may be a reflection of drilling operations and not entirely attributable to Mississippi River outflow.

Mississippi River outflow in the GOM is primarily influenced by a strong westward current along the Louisiana/Texas (LATEX) shelf as well as a northeastward current flowing alongside the Mississippi/Alabama/Florida (MAFLA) shelf [29]. The westward LATEX current explains the significant increase in trace metal concentrations west of the Mississippi River Delta. Outflow from the Mississippi River Delta is dominated by the westward current, carrying with it Mississippi-derived aluminosilicate compounds, resulting in higher metal concentrations west of the river delta. Similarly, Holmes [30] found an increase in trace metals (Ba, Cr, Cu, Ni, Pb, and V) in the northwestern GOM shelf, when compared with the southeastern GOM shelf. In addition, Wade et al. [20] found that Be, Co, Cr, Fe, Si, Tl, V, Zn, K, and Mg correlated with Al and were derived from Mississippi River lithogenic silicate material.

Strontium and Ca are chemically similar, showing a high affinity for carbonate, rather than fine silicate material. Therefore, the negative correlation of Sr and Ca with Al and other trace metals and the sharp increase in Sr and Ca concentrations east of site 86 are likely due to this relationship. Sediments in the eastern GOM have higher carbonate levels primarily derived from calcium carbonate

shells of planktonic foraminifera and coccolithophores [30–32]. Morse et al. [31] reported that the majority of carbonate minerals in marine sedimentary environments are biogenic in origin, precipitated by living organisms. Though Sr and Ca are largely derived from river output [33], these metals are not influenced by organic carbon, silt + clay, or fine silicate material, and therefore settling and distribution of these metals in marine sediments are likely attributable to the availability of carbonate material [19]. This explains the elevated concentrations of Sr and Ca observed in eastern areas of this study, where carbonate is more prevalent. The natural groupings of metals observed in the present study are supported by the findings of many previous studies [19, 20, 27, 30].

The mean concentrations of Ba, Cr, Cu, Ni, Pb, V, and Zn in the current study were lower than those reported from the northern GOM slope by Wade et al. [20]. However, our values are grouped into high and low concentrations based on location, so mean values are of limited use. The higher concentrations for these trace metals, found in the western sites, are more comparable to the aforementioned report [20]. Concentrations of Cr, Cu, Pb, and Zn were below the NOAA aquatic-life benchmark lower screening value for sediment contamination. Nickel concentrations at most western sites exceeded the aquatic-life benchmark lower screening value (20.9 mg/kg), but all concentrations were below the upper screening value (51.6 mg/kg) for sediment contamination predicted to have effects on aquatic organisms [34]. Vanadium concentrations in several western sites exceeded the EPA chronic exposure benchmark (57 mg/kg), while all eastern sites were below this benchmark [35]. Wade et al. (2008) found a mean Ni concentration of 38 mg/kg and a mean V concentration of 100 mg/kg for the northern GOM shelf and slope [20]. Various other studies also reported higher yet comparable values for Ni and V than those reported in the current study [36–39]. The strong correlation of Ni and V with Al in this study suggests that the concentrations of these metals are mostly attributable to natural aluminosilicate minerals [20, 40]. These concentrations may also be enhanced in Louisiana due to drilling activity and adsorption to the fine sediment in the area.

Barium concentrations in this study ranged from 5 to 1,124 mg/kg; however, many sites in the GOM contain Ba concentrations in excess of tens of thousands of mg/kg [16, 41]. The values found in this study are similar to that of a previous study in the Southern California Bight, where Ba concentrations ranged from 43 to 1,899 mg/kg in benthic sediments and from 145 to 1,259 mg/kg in intertidal sediments [42, 43]. Higher concentrations are usually found near drilling platforms and other drilling operations [16, 43]. A study in the Santa Maria Basin off the west coast of California yielded Ba concentrations of 923 mg/kg within a 500 m distance from a drilling platform and 869 mg/kg at 1000 m from the platform [43, 44]. The sites with the highest concentrations of Ba in this study were within the general proximity of the most Ba-enriched sites reported by the U.S. Department of the Interior's Minerals Management Service, in an area of intense petroleum exploration [41].

Strontium concentrations in this study ranged from 53 to 1,863 mg/kg and were much higher in the eastern shelf areas. Calcium was also much higher in eastern shelf areas, ranging from 4,120 to 235,362 mg/kg. Similarly, Holmes [30] reported mean Sr concentrations of 198 mg/kg and 1,060 mg/kg for the northwestern and northeastern GOM shelf/slopes and mean Ca concentrations of 15,800 mg/kg to 286,000 mg/kg in western Gulf versus Florida shelf sediments.

Total PAHs were negatively correlated with N : C; however, all PAHs in this study were well below the benchmark value (PAH lower screening value: 4,022 μg/kg) for sediment contamination expected to cause biological effects [34]. A previous study also determined that PAHs in coastal Louisiana and Mississippi sediments collected in 2012 were well below the level expected to cause effects [45]. Therefore, the negative correlation of N : C with PAHs was likely due to a difference in sediment grain size preference rather than a direct effect of PAHs. The low PAH concentrations detected in this study coincide with low (0.3–1.4%) organic carbon levels. Natter et al. [46] found that oiled sediments from coastal marshes in Alabama, Louisiana, and Mississippi contained significantly higher levels of organic carbon (10–28%) than unpolluted sediments (<3%).

Meiofauna correlations with sediment characteristics reported herein are consistent with previous studies. Those studies have reported increased copepod grazing in sediments with larger grain sizes [47], while nematodes thrive in siltier sediments that are rich in organic matter [6, 48]. In the current study, the highest copepod densities were observed in eastern study sites, where silt + clay percentage greatly decreased and the sandier sediments became more prevalent. Increased nematode density was observed in western study sites, where silt + clay was dominant and high organic carbon and trace metal concentrations were found. The relationship between silt + clay percentage, organic carbon, and Al is supported by earlier work that demonstrated a direct relationship between these variables in coastal sediments [27]. Their research suggested that Al could be used as a surrogate for grain size analysis because of these strong correlations. Nematode densities now appear to fit within that relationship with silt + clay percentage, organic carbon, and Al. No such clear relationship between copepods, trace metals, and granulometry was found in the current study, though copepod density did correlate with the very coarse + coarse sand type (which revealed no clear distribution pattern). Overall, nematodes and copepods appear to be influenced by sediment grain size and organic carbon rather than sediment pollutants.

Raw data from a three-year (2007–2009) meiofauna study by Landers et al. [49] was reexamined to focus only on those locations within the same longitudinal range as in the current study. This examination revealed a mean of 85 nematodes/10 cm^2 and 6 copepods/10 cm^2, while the current study reports 159 nematodes/10 cm^2 and 11 copepods/10 cm^2. The nematode densities were particularly higher in sites 73–86 compared to similar sites from 2007 to 2009 (233 nematodes/10 cm^2 in 2012 versus 87 nematodes/10 cm^2 in 2007–2009). Recent collections using a multicorer from these locations may help to explain this variation.

Findings from the current study were comparable to those of previous meiofauna studies on continental shelf and slope systems in various parts of the world. Netto et al. [50] found mean densities similar to the current study, with 129 nematodes/10 cm^2 and 16 copepods/10 cm^2 on the continental slope near the coast of southeastern Brazil, at a depth of 215 (±14) m. In a Kenyan continental slope study in the western Indian Ocean, nematode densities ranged from 276 to 944 individuals/10 cm^2, though they reported that these numbers were higher due to conspicuously higher densities observed at 20 m depths (significantly shallower than any samples from the current study) [51]. At sites from the northeast Atlantic shelf break, a mean nematode density of 250 individuals/10 cm^2 was observed [52]. In sediments from the western continental shelf of India in the Arabian Sea, nematode densities ranged from about 100 to 300 individuals/10 cm^2, with the lower densities observed in sandy sediments and the highest in silt + clay sediments. Copepods showed a reverse trend as they were more prevalent in sandy sediments [53]. This link between meiofauna and sediment grain size supports the current study's findings. Nematodes and copepods of the GOM continental shelf show no indication of changes in abundance attributable to sediment pollutants, which were found at relatively low levels when compared with benchmarks and findings from previous studies, and therefore do not appear to have been affected by anthropogenic disturbance.

5. Conclusions

This study documents the two distinct sediment zones that exist along the continental shelf of the northern Gulf of Mexico. The shelf sediments in the western study area were heavily influenced by runoff from the Mississippi River, while sediments in the eastern study area were influenced by naturally occurring carbonate material. Meiofauna densities appeared to be most influenced by sediment type and not trace metals or PAHs.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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