Gulf of Mexico Science

Volume 32
Number 1 *Number 1/2 (Combined Issue)*

Article 1

2014

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DOI: 10.18785/goms.3201.01

Recommended Citation

Landers, S. C., A. C. Nichols, C. A. Schimmer, P. M. Stewart, S. Ramroop, D. A. Steffy and F. A. Romano III 2014. Meiofauna and Trace Metals From Sediment Collections in Florida After the Deepwater Horizon Oil Spill. Gulf of Mexico Science 32 (1). Retrieved from https://aquila.usm.edu/goms/vol32/iss1/1

Gulf of Mexico Science, 2014(1–2), pp. 1–10

Meiofauna and Trace Metals From Sediment Collections in Florida After the Deepwater Horizon Oil Spill

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Sediment from the Florida Gulf continental shelf was collected from 18 sites during October and November 2010 for meiofauna and trace-metals analysis. Collections were obtained using a Shipek® grab on the National Oceanic and Atmospheric Administration ship *Pisces* and spanned from the head of the DeSoto Canyon to off the southern end of the Florida peninsula approximately following the 100–200-m contour. Mean abundance of the dominant meiofaunal groups (nematodes, copepods, and polychaetes) was unchanged when compared with 2007–2009 data. Nematodes and copepods correlated positively with each other, and negatively with latitude and longitude, suggesting that there were higher densities in southern Florida. These results contrast with those from 2007–2009 in that previously nematodes had no correlation with latitude or longitude in Florida. Nickel (Ni) and vanadium (V) concentrations were higher in the western Florida locations and correlated positively with increasing depth. No relationship was found between Ni, V, and meiofauna densities.

Introduction

Recent work after the Deepwater Horizon oil spill (DHOS) has reported changes in the Gulf of Mexico sediment. Those studies revealed increases in polycyclic aromatic hydrocarbons (PAH) and trace-metal concentrations in oiled sediment (Natter, 2012) and changes in the microbial community, including prokaryote biomass, ciliate biomass (Ortman et al., 2012), increases in fungal communities (Bik et al., 2012), and concentrations of *Vibrio vulnificus* within DHOS tar balls (Tao et al., 2011). Meiofauna studies after the DHOS are few, though recently significant shifts in shoreline nematodes, annelids, and flatworms have been reported when sediment from 2010 was compared before and after oiling from the DHOS (Bik et al., 2012). Additional studies have reported nematode and copepod communities along the edge of the continental shelf from postspill sediments in Louisiana (Landers et al., 2014) and affected meiofauna communities from deep sediments near the DHOS well head have been reported (Montagna et al., 2013). Prespill data for meiofauna exist for the northern Gulf continental shelf, which documented meiofauna distributional trends during 2007–2009 (Landers et al., 2012). That study, which examined nematodes, benthic copepods, polychaetes, priapulid loricate larvae, mites, kinorhynchs, crustacean nauplii, and loriciferans, revealed a trend of higher animal abundances along the Florida escarpment than other areas of the Gulf continental shelf. Other prespill studies of meiofauna in the Gulf of Mexico analyzed abundances at specific sampling sites (Yingst and Rhoads, 1985; Montagna and Harper, 1996; Escobar-Briones et al., 2008) or transects and regions in the Gulf (Escobar et al., 1997; Baguley et al., 2006), and have reported variable animal densities related to several factors including depth, proximity to the Mississippi River, and toxicants in the sediment.

The present study analyzed sediment collected in October and November 2010 approximately 3 mo after the DHOS. Our study site approximately followed the 100–200-m depth contour on board the annual National Oceanic and Atmospheric Administration (NOAA) small pelagics fish-sampling cruise, as in previous years of study by our laboratory (Landers et al. 2012). The objectives were to examine whether the animal densities for meiofauna groups observed in 2007–2009 were similar to Florida collections from 2010. Additionally, we examined the relationship of meiofauna densities to nickel (Ni) and vanadium (V) concentrations in the same sediment, as these have been shown to accumulate at low levels in oil mousse and in sediments polluted by the DHOS (Floyd et al., 2012; Liu et al., 2012; Natter, 2012) and were the two trace metals targeted by the Environmental Protection Agency (EPA) for postspill analysis of Gulf sediment (USEPA, 2013a, b).

Methods

Meiofauna collection.—Sediment samples were collected using a Shipek® grab on the NOAA

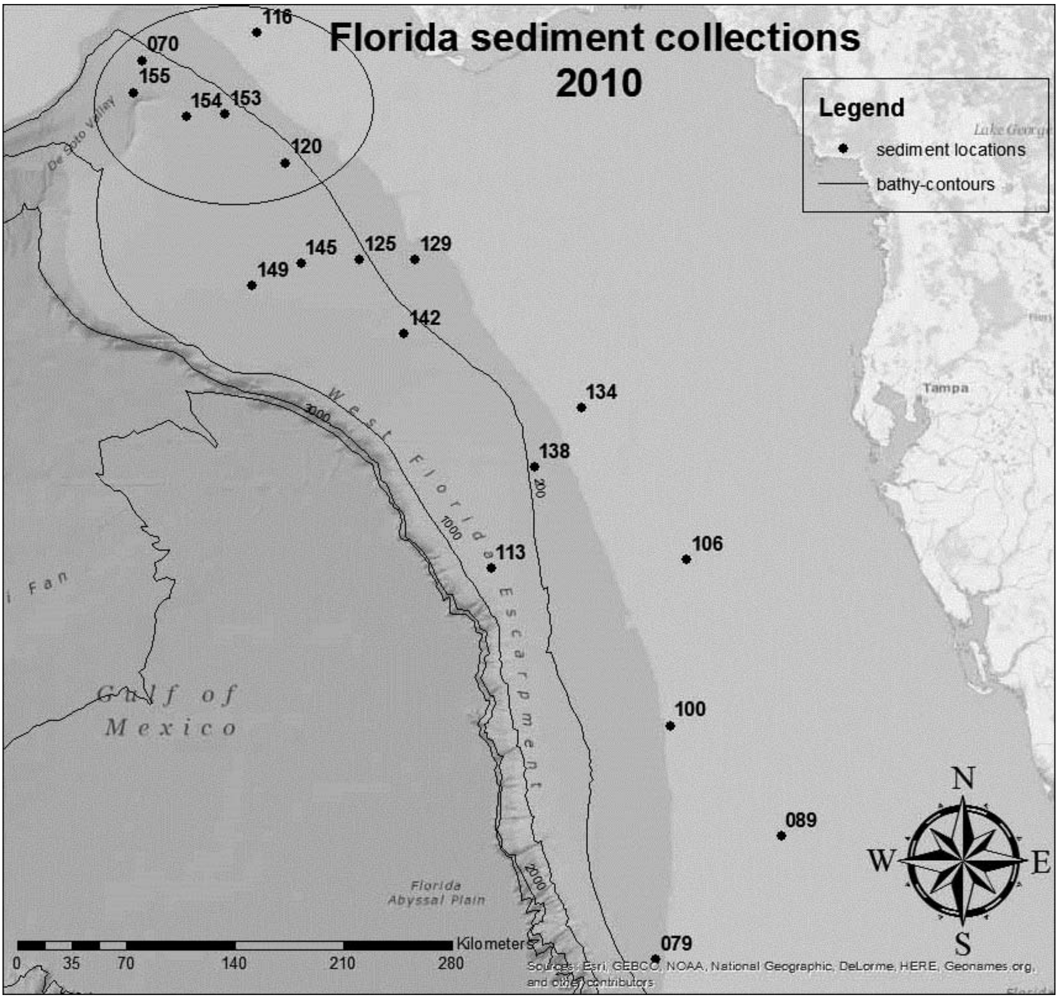

Fig. 1. Florida sediment collections 2010 (18 sites).

ship *Pisces*, which collects a sample to a depth of 10.2 cm. The sampling device does not preserve the loose flocculent layer resting on the top of the sediment, and thus our meiofauna collections reflect subsurface animal densities. Sample water depth varied from 56 to 457 m (mean = 226 m); bottom temperature varied from 8.9°C to 20.7°C (mean = 15.2°C); bottom salinity varied from 35.0 to 36.5 practical salinity units (psu) (mean = 35.9 psu). Collection sites were randomly selected by NOAA (approximately every third fish trawl station) during the annual

TABLE 1. Abundance of meiofauna in Florida (numbers represent mean # animals/10 cm^2). Rows represent: 1) means of all 18 sites from 2010, 2) means of all 50 cores obtained from the 18 sites in 2010, and 3) 2007–2009 means from 54 sites. Standard deviations are in parentheses. Nema = Nematoda, Cop = Copepoda, Poly = Polychaeta, Naup = nauplii, Kino = Kinorhyncha, Acar = Acari, Priap = Priapulida.

Year	Nema	Cop	Poly	Naup	Kino	Acar	Priap
2010	81.16	8.11	3.10	2.31	0.45	0.28	0.23
18 sites	(43.33)	(11.44)	(2.27)	(3.07)	(0.88)	(0.31)	(0.57)
2010	83.38	8.20	3.10	2.23	0.48	0.30	0.25
50 cores	(53.75)	(14.52)	(3.50)	(4.17)	(1.10)	(0.62)	(0.81)
2007–2009	79.53	9.98	3.39	2.39	0.26	0.15	0.30
54 sites	(56.09)	(14.59)	(2.34)	(7.86)	(0.52)	(0.41)	(0.76)

DOI: 10.18785/goms.3201.01

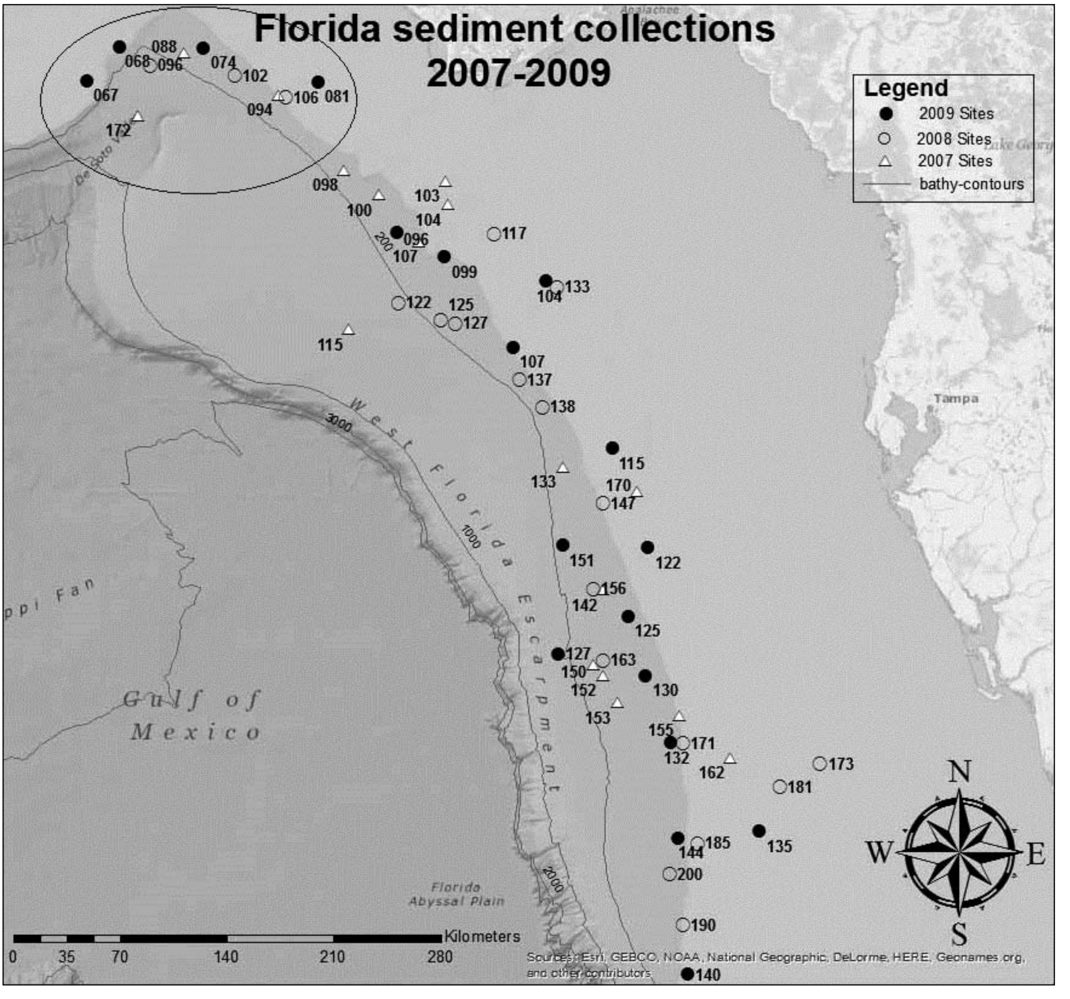

Fig. 2. Florida sediment collections 2007–2009 (54 sites).

TABLE 2. Spearman correlational analysis from 2010 sediment collections (n = 18). * = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.001$. Nema = Nematoda, Cop = Copepoda, Poly = Polychaeta, Naup = nauplii, Kino = Kinorhyncha, Priap = Priapulida, Acar = Acari, Lat = latitude, Long = longitude, DO_2 = dissolved oxygen, Sal = salinity, Temp = temperature, Depth = water depth.

Variable	Nema	Cop	Poly	Naup	Kino	Priap	Acar	Lat	Long	Ni	V
Cop	0.759***										
Poly	0.717**	0.768***									
Naup	0.545*	0.736***	0.554*								
Kino	0.531*	0.605**	0.380	0.613**							
Priap	0.520*	0.457	0.565*	0.074	0.364						
Acar	0.660**	0.837***	0.582*	0.507*	0.547*	0.384					
Lat	−0.639**	−0.695**	−0.585*	−0.372	−0.297	−0.286	−0.559*				
Long	−0.529*	−0.642**	−0.545*	−0.33	−0.380	−0.361	−0.406				
Ni	−0.253	−0.449	−0.373	−0.184	−0.369	−0.576*	−0.353	0.451	0.699**		
V	−0.088	−0.277	−0.061	−0.027	−0.110	−0.344	−0.207	0.395	0.589*	0.845***	
DO_2	0.12	0.290	0.106	0.161	0.21	0.238	0.156	−0.35	−0.645**	−0.858***	−0.836***
Sal	0.108	0.369	0.214	0.181	0.364	0.350	0.300	−0.286	−0.618**	−0.901***	−0.736**
Temp	0.143	0.384	0.250	0.174	0.378	0.395	0.302	−0.288	−0.628**	−0.911***	−0.744***
Depth	−0.152	−0.396	−0.282	−0.192	−0.413	−0.404	−0.298	0.309	0.655**	0.903***	0.711**

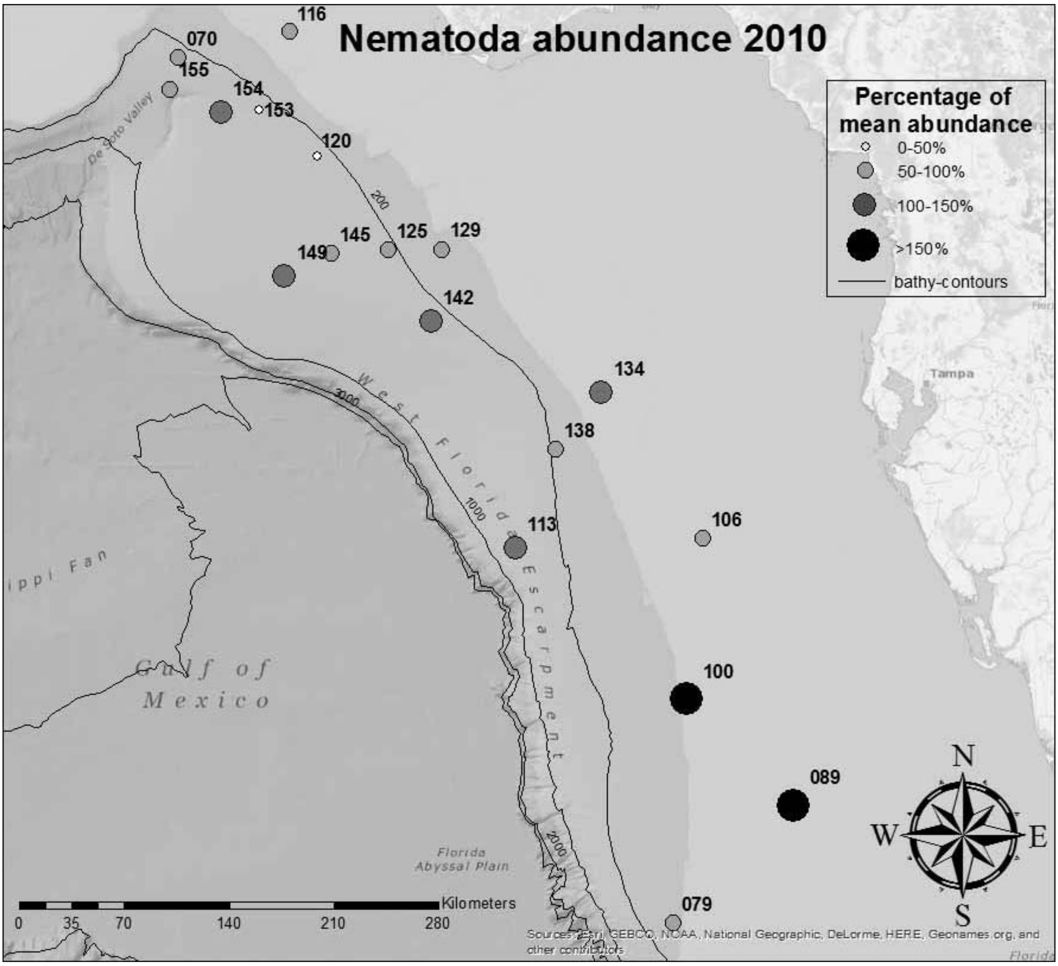

Fig. 3. Nematoda abundance in 2010, mapped as percentage above or below the mean for the study (mean # nematodes = 81.1/10 cm^2 core).

fish survey conducted by the National Marine Fisheries Service (NMFS) Pascagoula, MS laboratory in Oct. and Nov. 2010 (Fig. 1). Shipek grabs were subcored in triplicate for meiofauna analysis. The cores had a 4.4-cm diameter ($\sim$15.19 cm^2 area) and were made to a depth of 5 cm from the Shipek grab, identical to the sampling and coring methods used in our comparative 2007–2009 study (Landers et al. 2012). Sediment for metals analysis was obtained from the remaining sediment.

Meiofauna samples were fixed on board the ship in 10% formalin (5% final concentration), and later sieved (333 or 500 μm presieve and 63 μm final sieve) before concentrating the animals by Ludox® separation (Burgess, 2001; Montagna, 2001). The animals were stained with rose bengal and then counted using a counting wheel. Animal groups were identified using Higgins and Thiel (1988) and Giere (2008).

Trace-metal analysis.—Water-saturated sediments for metal analysis were collected from the Shipek grab sampler and placed in clear glass jars. The jars were labeled, sealed with a Teflon-lined lid, and placed in a 4°C walk-in cooler. Samples were transported to Jacksonville State University for processing. Air-dried sediment samples were subsampled into 1-g (± 0.001 g) triplicates. Samples were placed in acid-washed 150-ml beakers for digestion. All reagents used in sample preparation and metal analyses were trace-metal grade. Samples were digested using 15 ml of concentrated nitric acid, and further oxidized by the addition of 1 ml of hydrogen peroxide. The digested samples were diluted with 2 M sulfuric acid and filtered (Fisherbrand Q8 filter paper) into 50-ml volumetric flasks. Ultrapure water (17 MΩ resistance) was added to bring the total volume to 50 ml. Digested samples were submitted to Southern Environmental

DOI: 10.18785/goms.3201.01

TABLE 3. Trace-metal (mg/kg) and meiofauna (#/10 cm^2) data from 18 Florida sediment collections. Site numbers correspond to locations in Figure 1.

Site number	Latitude	Longitude	Depth (m)	Ni	V	Nematoda density	Copepoda density
070	29.6599	−86.9511	232.0	7.95	5.50	43.01	2.63
079	25.0453	−83.9790	121.0	2.30	1.55	75.26	19.96
089	25.6878	−83.2580	56.0	1.33	6.55	140.88	43.01
100	26.2623	−83.8989	110.0	0.99	2.41	189.15	14.26
106	27.1196	−83.8039	58.0	2.55	4.53	66.49	26.99
113	27.0745	−84.9303	457.0	12.22	7.32	85.3	2.63
116	29.8003	−86.2845	71.0	2.85	3.65	53.54	0
120	29.1440	−86.1210	243.0	9.63	6.32	16.23	1.09
125	28.6513	−85.6930	214.0	9.85	9.28	63.19	4.16
129	28.6537	−85.3708	156.0	8.88	8.18	74.82	3.07
134	27.8972	−84.4130	78.0	1.52	1.66	121.13	4.60
138	27.5958	−84.6840	194.0	7.63	6.35	50.25	1.09
142	28.2778	−85.4367	272.0	8.10	7.88	110.16	7.89
145	28.6324	−86.0332	309.0	11.63	8.52	62.76	0.43
149	28.5192	−86.3151	443.0	17.82	12.15	120.69	4.38
153	29.3899	−86.4693	259.0	11.18	10.07	22.05	0
154	29.3747	−86.6962	382.0	14.65	11.75	103.35	9.21
155	29.4978	−87.0018	408.0	11.52	9.42	62.54	0.658
Mean				7.92	6.83	81.16	8.11

Testing, Inc. (Florence, AL) for inductively coupled plasma (ICP) analysis using EPA *Methods for Chemical Analysis of Water and Wastes*, EPA-600/4-79-020, revised May 1994. All samples were run in batches that included blanks (reagent and instrument) and supplemented samples.

Statistical analysis.—Animal abundance and trace-metal concentrations were analyzed using SPSS 11.0® software. Cross-correlation analysis was used to examine the 18 grab-site means from 2010. Because of lack of normality and homogeneity of variances, the nonparametric Mann–Whitney U-test was used to examine differences in nematode and copepod densities in North Florida locations before and after the oil spill. All 2010 site means for animal abundance were calculated from at least two cores from each grab, with the exception of site 155, which had only one meiofauna core (50 total cores were analyzed from 18 sites). Maps were constructed with ArcGIS® 10 using site means for metals concentration or meiofauna abundance. Data from our previous samplings in Florida (2007–2009) were used for comparative purposes (Landers et al. 2012).

RESULTS

Statistical analysis.—Collections from Florida in 2010 produced similar mean meiofauna densities as in 2007–2009 (Table 1). Additionally, site means (n = 18) for animal abundances were similar to the core (n = 50) means. The site means were used for the statistical correlations (Table 2).

Spearman cross-correlation analysis from the Florida 2010 samples revealed correlations between many variables (Table 2). Nematode and copepod abundance (>93% of the meiofauna) were negatively correlated with latitude and longitude (to avoid confusion, longitude was converted to positive (west) values for our analysis, e.g., 83°W instead of −83°), as these animals were more abundant in the southern and eastern regions of the sampling area. The trend for increased abundance at lower latitude and eastern longitude (southern Florida) was also evident for polychaetes. The dominant members of the meiofauna—nematodes, copepods, polychaetes, and nauplii—all correlated positively with each other. Additionally, nematodes correlated positively with other minor meiofauna groups: kinorhyncha, priapulida loricate larvae, and acari. Water depth was not significantly related to any meiofauna group (Table 2), but was examined because many western sites were deeper than the eastern sites. It was thought that this variable could confound any correlations between meiofauna and longitude. Northern locations near the DeSoto Canyon (where surface oiling was known to occur) did not show a significant difference in nematode and copepod density after the DHOS (circled locations on Fig. 1) vs before (circled locations on Fig. 2) when analyzed with the Mann–Whitney U-test (Nematoda: $P = 0.158$, Copepoda: $P = 0.115$).

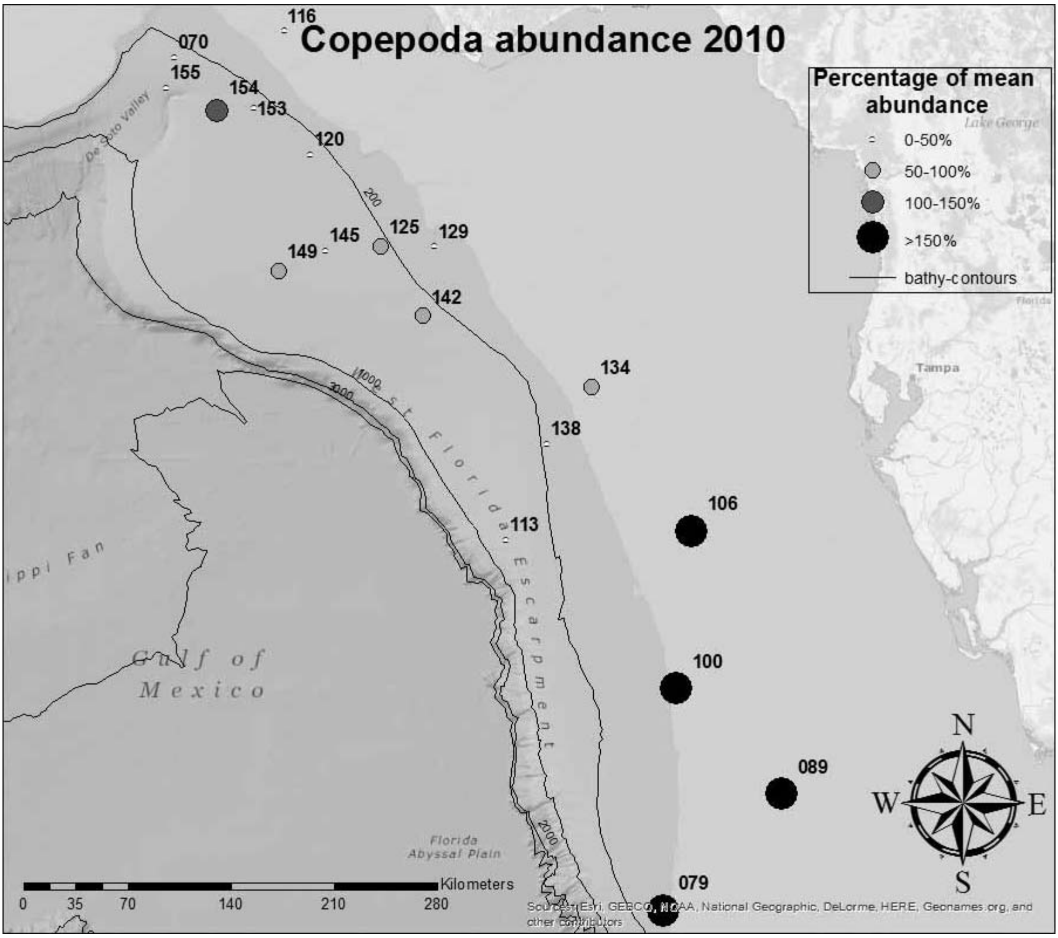

Fig. 4. Copepoda abundance in 2010, mapped as percentage above or below the mean for the study (mean # copepods = 8.1/10 cm^2 core).

Nickel and vanadium concentrations (Tables 2 and 3) demonstrated the opposite trend than meiofauna abundance with respect to longitude. These metals correlated positively with longitude, indicating that there were higher levels in the western area of the study. Although the western sites were also more northern, Ni and V did not correlate with latitude. These two metals correlated positively with increasing water depth, and thus, negatively with dissolved oxygen, temperature, and salinity (salinity and depth had a very strong negative correlation [$r = -0.990$, $P < 0.001$]). Meiofauna abundance did not correlate significantly with Ni or V.

Abundance and distribution.—Maps of the 2010 (Fig. 1, 3–6) and 2007–2009 (Fig. 2) Florida collections show the sampling locations from the DeSoto Canyon to southern Florida. Nematode and copepod abundance maps were constructed to show the percentage of the mean for all sites. Maps of Ni and V concentrations by location were constructed to show concentrations relative to the mean for the 18 sites in the study. These maps support the findings revealed by the statistical tests, in that the metal concentrations tended to increase in the western, deeper sites and the animal concentrations tended to increase in the eastern areas. Nematodes, the dominant meiofauna group, and copepods both had a negative correlation with latitude and longitude, which is reflected in Figs. 3 and 4.

Discussion

This study demonstrated that the dominant meiofauna, nematodes and copepods, are more abundant in the eastern areas of the Florida Gulf continental shelf, whereas Ni and V concentrations are higher in the western areas and also correlate

DOI: 10.18785/goms.3201.01

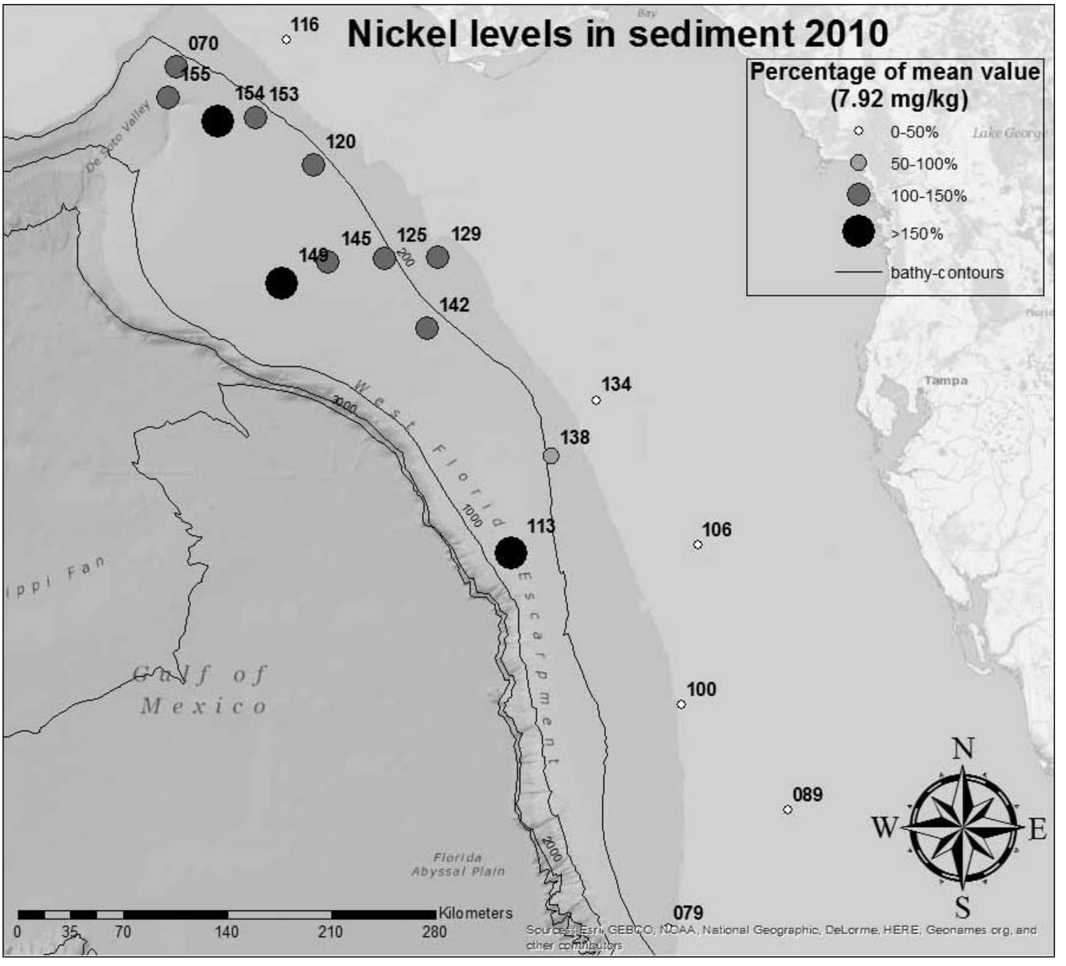

Fig. 5. Nickel concentrations in 2010, mapped as percentage above or below the mean (7.92 mg/kg) for the study.

with increased depth. Data from 2007–2009 (Landers et al., 2012) show a similar trend of higher copepod densities in eastern Florida locations, but nematodes did not have this distribution trend earlier. Additionally, this study has shown little change in the overall meiofauna densities along the Florida Gulf shelf when 2010 data are compared with data from 2007–2009 (Landers et al., 2012).

Nickel and vanadium are found in concentrations above background levels in oil and can sometimes be used to infer oil pollution (Lewan, 1984), whether originating from natural seeps, spills, or contamination from drilling operations. As offshore drilling is not permitted by law within Florida state waters, oil, if present, would most likely have originated from a spill or from seeps. The 2010 Deepwater Horizon blowout led to over 4.4 million barrels of oil being released into the Gulf of Mexico (Crone and Tolstoy, 2011). The deep benthic footprint of the oiling did not approach the Florida escarpment (Montagna et al., 2013), though the surface oiling extended from Louisiana eastward to Apalachicola, Florida (OSAT, 2010), and simulation models have suggested the plausibility of oil contamination on the West Florida continental shelf (Weisberg et al., 2014), making a survey of meiofauna and trace metals from the northern and southern Florida continental shelf important. Oil from the DHOS (MC252) is classified as Louisiana Light Sweet Crude, and is known to have low levels of V (0.2 mg/kg) and Ni (1.5 mg/kg) (Liu et al. 2012), though these metals have been shown to concentrate to higher levels in weathering oil or oil within sediments. Specifically, at the oil-affected site Bay Jimmy South (Barataria Bay area, Louisiana), V concentrations

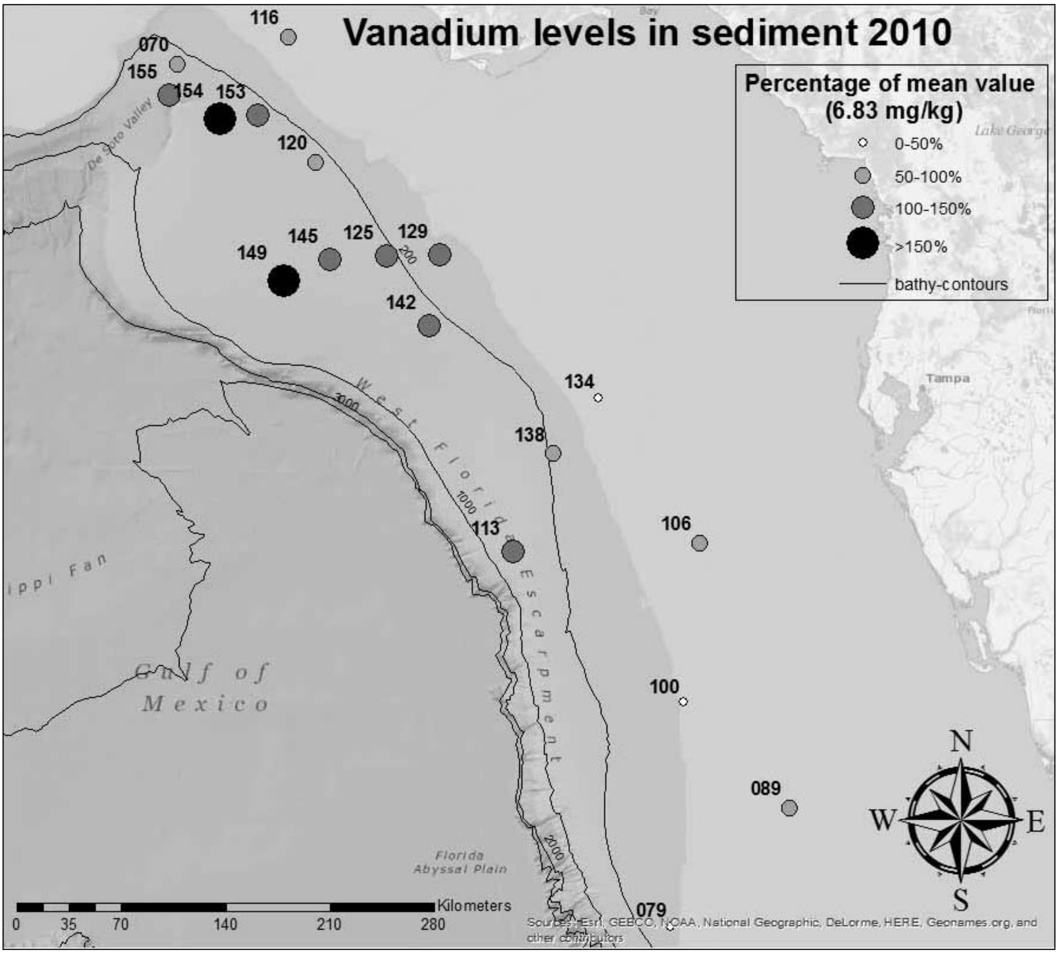

Fig. 6. Vanadium concentrations in 2010, mapped as percentage above or below the mean (6.83 mg/kg) for the study.

in the sediment were ~20 mg/kg from the surface down to a depth of 10 cm and Ni concentrations were ~13 mg/kg from the surface down to a 10-cm depth (Natter 2012). Our sampling collected sediment from the top 10 cm of the seafloor (top 5 cm for meiofauna), and detected a high concentration of 12.15 mg/kg for V (mean = 6.83 mg/kg) and 17.82 mg/kg for Ni (mean = 7.92 mg/kg) (Table 3 and Figs. 5, 6). These values are low but not inconsistent with data reported by the EPA nearshore sediment sampling from Escambia County (Pensacola) to Taylor County (east of Tallahassee), Florida (6 June 2010 to 29 Sep. 2010) (USEPA 2013b). None of the V or Ni levels in this current report exceeded EPA sediment chronic exposure benchmarks for aquatic life (57 mg/kg for V and 20.9 mg/kg for Ni) (USEPA 2013a). Our laboratory has found that an alternate method for trace-metal detection using high-temperature digestion and EPA ICP method 200.7 can increase trace-metal detection by a factor of two to three (Landers et al. 2014), which could result in some of our northern collection sites exceeding the EPA benchmark for Ni. However, we found no relationship between meiofauna densities and trace metals in the current study.

Recent data collected from 2012 have revealed elevated Ni and V in Louisiana sediments along the 100–200-m contour (Landers et al., 2014), but those metal concentrations are likely due to binding to aluminosilicate compounds flowing out of the Mississippi River. Nickel and vanadium from the northern Florida sediments collected in 2012 and 2013 near sites from the current study are consistent with 2010 data herein and suggest that the trace metals represent background levels expected in carbonate sediments (personal observations). Thus, Ni and V levels in the sediment

DOI: 10.18785/goms.3201.01

decrease along the continental shelf from Louisiana to Apalachicola, and further decrease along the Florida peninsula toward the south.

In summary, our study examined meiofauna densities from collections made before and after the DHOS and compared their densities with concentrations of the trace metals Ni and V. We report little change in meiofauna densities, along with low levels of Ni and V in our sediment collected in fall 2010. Oil contamination at our collections sites would likely have altered the meiofauna communities, as reported by others earlier. Previous reports suggested that sensitive and resistant meiofauna species reacted differently to PAH (Carman et al., 1997, Millward et al., 2004). In some cases, oil exposure positively correlated with meiofauna densities, possibly due to increased microbial activity due to the increased available carbon serving as a food source for the bacteria and eventually for the meiofauna (Fleeger and Chandler, 1983, Montagna et al., 1987). Deep benthic meiofauna communities very close to the DHOS well head (within 15 km) have elevated nematode:copepod ratios and have elevated nematode densities but lower species diversity in the affected areas (Montagna et al., 2013). Species compositional changes in the meiofauna may therefore be influenced by new food sources and variable susceptibility to pollution. The effects of the DHOS on the meiofauna are not restricted to the deep communities but also occur on the shoreline, as a change in nematode diversity in coastal Alabama has been reported after the DHOS (Bik et al., 2012).

Acknowledgments

This research was made possible by a grant from BP/The Gulf of Mexico Research Initiative. The authors thank the students and technicians at Troy University and Jacksonville State University who assisted with sediment collection and laboratory work. We also thank the NOAA/NMFS Pascagoula Laboratory for ship time and the crew and scientists aboard the NOAA ship *Pisces* for assistance with sediment collection and providing supporting data. Portions of the comparative data used in this report (2007–2009 Florida data) have been published earlier.

Literature Cited

Baguley, J. G., P. A. Montagna, L. J. Hyde, R. D. Kalke, and G. T. Rowe. 2006. Metazoan meiofauna abundance in relation to environmental variables in the northern Gulf of Mexico deep sea. Deep-Sea Res. I 53:1344–1362.

Bik, H. M., K. M. Halanych, J. Sharma, and W. K. Thomas. 2012. Dramatic shifts in benthic microbial eukaryote communities following the deepwater Horizon Oil Spill. PLoS ONE 7(6):e38550. doi:10.1371/journal.pone.0038550.

Burgess, R. 2001. An improved protocol for separating meiofauna from sediments using colloidal silica sols. Mar. Ecol. Prog. Ser. 214:161–165.

Carman, K. R., J. W. Fleeger, and S. M. Pomarico. 1997. Response of a benthic food web to hydrocarbon contamination. Limnol. Oceanogr. 42:561–571.

Crone, T. J., and M. Tolstoy. 2011. Magnitude of the 2010 Gulf of Mexico oil leak. Science 330:634.

Escobar, E., M. Lopez, L. A. Soto, and M. Sinoret. 1997. Density and biomass of the meiofauna of the upper continental slope in two regions of the Gulf of Mexico. Cienc. Mar. 23:463–489.

Escobar-Briones, E. G., C. Díaz, and P. Legendre. 2008. Meiofaunal community structure of the deep-sea Gulf of Mexico: variability due to the sorting methods. Deep-Sea Res. II 55:2627–2633.

Fleeger, J. W., and G. T. Chandler. 1983. Meiofauna responses to an experimental oil spill in a Louisiana salt marsh. Mar. Ecol. Prog. Ser. 11:257–264.

Floyd, E. L., C. T. Lungu, and J. M. Gohlke. 2012. An evaluation of nearshore sediment data after the Deepwater Horizon blowout. J. Environ. Sci. Eng. A 1:341–350.

Giere, O. 2008. Meiobenthology: the microscopic motile fauna of aquatic sediments. 2d ed. Springer, Berlin.

Higgins, R. P., and H. Thiel. 1988. Introduction to the study of meiofauna. Smithsonian Institution Press, Washington, DC.

Landers, S. C., A. C. Nichols, N. K. Barron, C. A. Schimmer, R. Tao, K. Yu, P. M. Stewart, and E. Ólafsson. 2014. Nematode and copepod diversity (2012) from Louisiana near the Deepwater Horizon oil spill. Proc. Biol. Soc. Wash. 127:47–57.

———, F. A. Romano III, P. M. Stewart, and S. Ramroop. 2012. A multi-year survey of meiofaunal abundance from the northern Gulf of Mexico continental shelf and slope. Gulf Mex. Sci. 30:20–29.

Lewan, M. D. 1984. Factors controlling the proportionality of vanadium to nickel in crude oils. Geochim. Cosmochim. Acta 48:2231–2238. doi:10.1016/0016–7037(84)90219–9.

Liu, Z., J. Liu, Q. Zhu, and W. Wu. 2012. The weathering of oil after the Deepwater Horizon oil spill: insights from the chemical composition of the oil from the sea surface, salt marshes, and sediments. Environ. Res. Lett. 7:035302. doi:10.1088/1748-9326/7/3/035302.

Millward, R. N., K. R. Carman, J. W. Fleeger, R. P. Gambrell, and R. Portier. 2004. Mixtures of metals and hydrocarbons elicit complex responses by a benthic invertebrate community. J. Exp. Mar. Biol. Ecol. 210:115–130.

Montagna, P. A. 2001. Field and laboratory methods for meiofaunal research, p. 491–499. *In:* Manual of environmental microbiology. 2nd ed. C. J. Hurst and R. L. Crawford (eds.). ASM Press, Washington, DC.

———, J. G. Baguley, C. Cooksey, I. Hartwell, L. J. Hyde, J. L. Hyland, R. D. Dalke, L. M. Kracker, M. Reuscher, and A. C. E. Rhodes. 2013. Deep-sea benthic footprint of the Deepwater Horizon blowout. PLoS ONE 8(8):e70540. doi:10.1371/journal.pone.0070540.

———, J. E. Bauer, J. Toal, D. Hardin, and R. G. Spies. 1987. Temporal variability and the relationship between benthic meiofaunal and microbial populations of a natural coastal petroleum seep. J. Mar. Res. 45:761–789.

———, and D. E. Harper. 1996. Benthic infaunal long term response to offshore production platforms in the Gulf of Mexico. Can. J. Fish. Aquat. Sci. 53:2567–2588.

Natter, M. G. 2012. Fate and transformation of oils and trace metals in Alabama and Louisiana coastal marsh sediments associated with the British Petroleum Gulf oil spill. M.S. thesis, Auburn Univ., Auburn, Alabama.

Operational Science Advisory Team (OSAT), U.A.C.: Summary report for subsea and subsurface oil and dispersant detection: sampling and monitoring, Paul F. Zukunft, RADM, U.S. Coast Guard, Federal On-Scene Coordinator, Deepwater Horizon MC252, 2010.

Ortmann, A. C., J. Anders, N. Shelton, L. Gong, A. G. Moss, and R. H. Condon. 2012. Dispersed oil disrupts microbial pathways in pelagic food webs. PLoS ONE 7(7):e42548. doi:10.1371/journal.pone.0042548.

Tao, Z., S. Bullard, and C. Arias. 2011. High numbers of *Vibrio vulnificus* in tar balls collected from oiled areas of the North-Central Gulf of Mexico following the 2010 BP Deepwater Horizon Oil Spill. Ecohealth. doi:10.1007/s10393-011–0720–z.

United States Environmental Protection Agency (USEPA). 2013a. Sediment benchmarks for aquatic life. *In:* EPA response to BP spill in the Gulf of Mexico. Accessible at: <http://www.epa.gov/bpspill/sediment-benchmarks.html >

———. 2013b. Coastal sediment sampling. *In:* EPA response to BP spill in the Gulf of Mexico. Accessible at: <http://www.epa.gov/bpspill/sediment.html >

Weisberg, R. H., L. Zheng, Y. Liu, S. Murawski, C. Hu, and J. Paul. 2014. Did Deepwater Horizon hydrocarbons transit to the west Florida continental shelf? Deep-Sea Res. II. In press. doi:10.1016/j.dsr2.2014.02.002.

Yingst, J. Y., and D. C. Rhoads. 1985. The structure of soft-bottom benthic communities in the vicinity of the Texas Flower Garden Banks, Gulf of Mexico. Estuar. Coast. Shelf Sci. 28:569–592.

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DOI: 10.18785/goms.3201.01