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Original Articles

Resilience of benthic foraminifera in the Northern Gulf of Mexico following the Deepwater Horizon event (2011–2015)

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ABSTRACT

Benthic foraminifera (BF) have been commonly used as marine petroleum contamination indicators. The Deepwater Horizon (DWH) released 4.0 million barrels of petroleum into the northern Gulf of Mexico (nGoM) over 87 days in 2010, causing Marine Oil Snow Sedimentation and Flocculent Accumulation (MOSSFA). Previous BF studies have documented region-specific impacts associated with contaminant input and sediment redox conditions. This study determined benthic resilience as measured by BF test density, species richness and heterogeneity. Surface sediment samples (0–42 mm) from seven sites throughout the nGoM (2011–2015) showed a continuous increase in mean species richness (27.2% ± 3.6%) and heterogeneity (19.8% ± 0.2%). The greatest increase occurred from 2011 to 2013, followed by consistent values from 2013 to 2015, which suggested a resilience rate on the order of three years. This study demonstrated the importance of long-term time-series studies following events such as DWH and exemplified necessity for broad baseline measurements prior to the next marine petroleum accident.

1. Introduction

Benthic faunae play essential roles in processes necessary for carbon controlling carbon degradation and preservation, food provision supporting the benthic dependent trophic hierarchy and detoxification of deep marine sediments (Danovaro et al., 2008; Levin and Dayton, 2009; Ramirez-Llodra et al., 2010, 2011; Jobstvogt et al., 2014; Thurber et al., 2014; Fisher et al., 2016). Benthic foraminifera are single-celled protists that are abundant throughout the global oceans from coastal to abyssal depths (Sen Gupta, 1999). Benthic foraminifera have commonly been used as indicators of anthropogenic environmental change such as coastal and estuarine pollution (Nigam et al., 2006) and estuarine and open marine oil contamination (Morvan et al., 2004; Mojtahid et al., 2006; Denoyelle et al., 2010; Brunner et al., 2013; Lei et al., 2015). During field observations following the Erika oil spill in the Bay of Bourgneuf, France (2000), anomalously low densities (1 indiv./cm^3) of benthic foraminifera were observed for a duration of 21 months after the spill (Morvan et al., 2004). Decreased benthic foraminiferal density has been correlated with proximity to petroleum drill cutting disposal sites off the coast of Congo (Mojtahid et al., 2006). At the same sites, the Foraminiferal Index of Environmental Impact (FIEI) positively correlated with proximity to petroleum drill cutting disposal (Denoyelle et al., 2010). The FIEI index also correlated with petroleum (polycyclic aromatic hydrocarbon) concentrations in the Bohai Sea, China following the Penglai oil spill in 2011 (Lei et al., 2015). These applications demonstrate the collective utility of benthic foraminiferal density and the formulation of diverse foraminiferal resilience indices as sensitive indicators of submarine oil contamination.

The Deepwater Horizon (DWH) event released 4.0 million barrels of oil into the northern Gulf of Mexico (nGoM) from April 20-July 12, 2010 (U.S. District Court, 2015). During and following the DWH, a phenomenon known as Marine Oil Snow Sedimentation and Flocculent Accumulation (MOSSFA) caused an order of magnitude increase in flocculent hydrocarbon flux and deposition throughout a large portion of the nGoM (Passow et al., 2012; Ziervogel et al., 2012; Brooks et al., 2015; Romero et al., 2015; Daly et al., 2016; Schwing et al., 2017; Romero et al., 2017). Increased flocculent hydrocarbon flux in the aftermath of the DWH resulted in a three-fold increase in polycyclic aromatic hydrocarbon (PAH) concentrations (Romero et al., 2015) as well as changes in redox conditions (Hastings et al., 2016), both of which affected the surface 4–12 mm of sediment (Brooks et al., 2015).

There was a subsequent 80–93% decline in benthic foraminiferal density at two sites in the nGoM up to 120 km northeast of the DWH wellhead in 2010 and early 2011 (Schwing et al., 2015). Schwing et al. (2015) suggested that this post-DWH decline was likely due to inhibited reproduction or mortality and associated with the intensification of reducing conditions and the 2–3 fold increase in sedimentary PAH concentrations resulting from the MOSSFA event. Initial signs of

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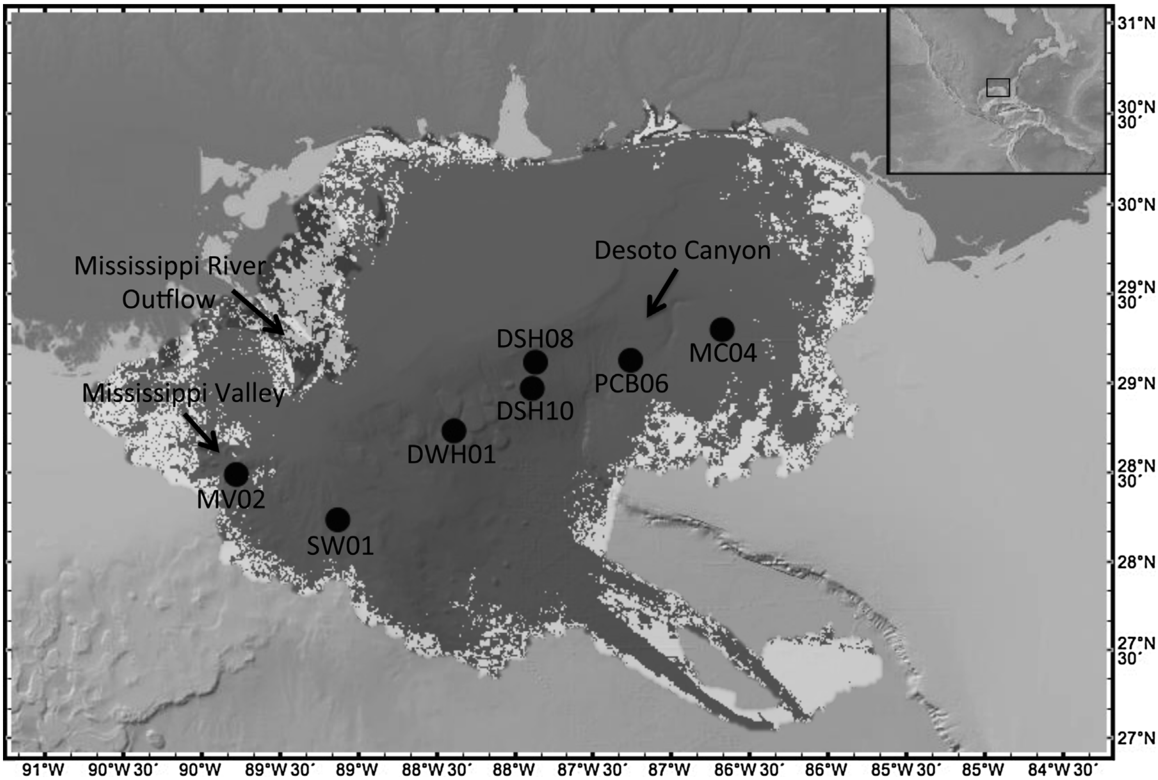

Fig. 1. Coring site locations in the northern Gulf of Mexico including bathymetric features such as the Mississippi Valley, DeSoto Canyon, and the Mississippi River Outflow. The dark gray overlay is the maximum extent of surface petroleum coverage (ERMA, 2015). (Note: DWH01 is less than 1 km from the Deepwater Horizon site for reference).

benthic foraminiferal resilience was observed at two sites in the nGoM in as short as two years after the DWH event, but the authors concluded that further work was needed to determine the full spatial extent and time-frame of recovery (Schwing et al., 2016a). This study builds on the results from previous studies by expanding the spatial coverage to seven sites throughout the nGoM and including records collected after August 2012, thereby providing a significantly broader scale and scope of study, both in a spatial and temporal context.

Following such a severe impact to the benthos resulting from the DWH event, it is important to characterize benthic resilience on large spatial and temporal scales. The purpose of this study was to use benthic foraminifera as indicators of benthic health and to assess benthic resilience following the Deepwater Horizon event throughout the nGoM from 2011 to 2015. This time series data and the characterization of the resilience of the benthos will serve as a new baseline of current conditions in the event of future petroleum releases.

2. Methods

Sediment cores were collected annually (2011–2015) from seven sites throughout the nGoM (Fig. 1, Table 1) using an Ocean Instruments MC-800 multicoring system, which collects eight cores (diameter: 10 cm, length: up to 70 cm) simultaneously. At each site, one core was utilized for benthic foraminiferal faunal analysis. Cores collected in 2011 were refrigerated (4 °C) and all subsequent collections were frozen (−20 °C) until sampled.

Cores were sub-sampled by extrusion at 2 mm intervals for the upper 50 mm, using a calibrated, threaded-rod extrusion device (Schwing et al., 2016b). Five sub-samples from the surface centimeter (0–2, 2–4, 4–6, 6–8 and 8–10 mm) and three sub-samples from downcore (20–22, 30–32, and 40–42 mm) were used for further analysis. Sub-samples were weighed and washed with a sodium hexametaphosphate solution through a 63-μm sieve to disaggregate detrital particles from foraminiferal tests (Osterman et al., 2003). The fraction remaining

Table 1
Core site name, latitude, longitude, water depth and collection dates.

Site Name	Latitude	Longitude	Water Depth (m)	Dates Collected
MC04	29.30	−86.68	401	Aug. 2013 Aug. 2014 Aug. 2015
MV02	28.49	−89.78	550	Aug. 2012 Aug. 2013 Aug. 2014 Aug. 2015
PCB06	29.13	−87.26	1043	Feb.2011 Aug. 2012 Aug. 2013 Aug. 2014 Aug. 2015
SW01	28.24	−89.13	1131	Apr. 2012 Aug. 2013 Aug. 2014 Aug. 2015
DSH08	29.12	−87.87	1143	Sept. 2011 Aug. 2012 Aug. 2013 Aug. 2014 Aug. 2015
DSH10	28.98	−87.89	1520	Sept. 2011 Aug. 2012 Aug. 2013 Aug. 2014 Aug. 2015
DWH01	28.74	−88.39	1577	Sept. 2011 Aug. 2012 Aug. 2013 Aug. 2014 Aug. 2015