Marine Pollution Bulletin 200 (2024) 116090

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Benthic foraminifera in Gulf of Mexico show temporal and spatial dynamics of microplastics

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ARTICLE INFO

Keywords:
Plastic pollution
Marine debris
Spatio-temporal
Sedimentary environment
Benthic organisms
Deep-sea

ABSTRACT

Microplastics have accumulated in the environment since plastic production began, with present-day observations that range from marine trenches to mountains. However, research on microplastics has only recently begun so it is unclear how they have changed over time in many oceanic regions. Our study addressed this gap by quantifying the temporal and spatial dynamics of microplastics in two deep-water regions of the Gulf of Mexico (GOM). We isolated agglutinated foraminifera from sediment cores and assessed microplastics that were incorporated into their tests. Our results indicated that microplastics were incorporated by agglutinated foraminifera after plastic production began. Microplastics were higher at deep-water sites and closer to the Mississippi River. This study confirms the presence of microplastic incorporation into agglutinated foraminifera tests and investigates microplastics in deep-water sediments in the GOM. Additional work is needed to fully identify the distribution of microplastics across the GOM and other oceanic basins.

1. Introduction

Microplastics, plastic particles <5 mm, are pollutants that have been observed in every global environment including the atmosphere, mountains, and marine trenches (Rios Mendoza et al., 2021). Their abundance has increased exponentially since the 1950s when mass plastic production began (Thompson et al., 2004; Uddin et al., 2021). Sediments can be used to determine spatial and temporal dynamics of microplastic accumulation on the seafloor, but prior research has focused largely on surface layers and shallow environments. In comparison, deep sediments (from shelf to slope, >200 m depth) have been relatively understudied (Uddin et al., 2021). Additionally, microplastics can exhibit high spatial variability so it is essential to expand studies across locations to understand the occurrence and distribution of this pollutant (Yao et al., 2019; Uddin et al., 2021). To address this gap, we assessed the temporal dynamics of microplastics from oceanic sediments in parts of a marine basin where microplastics are understudied.

Historically, the primary method used to determine the temporal dynamics of microplastics has been through analysis of specimen samples. For example, plankton samples revealed that macro- and microplastics in the North Atlantic Ocean and the North Sea have increased since the late 1950s, a trend which has tracked the exponential increase of plastic production (Thompson et al., 2004; Ostle et al., 2019). More recently, oceanic sediments have been analyzed to assess historical records of microplastics because they can act as sinks for various pollutants (Louvado et al., 2015; Rabotyagov et al., 2020; Scircle, 2020). Sediment cores can be used to reconstruct microplastic presence and abundance over long timescales and have revealed increased concentrations through time (Yao et al., 2019). Indeed, microplastics in sediments have increased threefold in 16 years on Belgian beaches (Claessens et al., 2011) and sixfold over 50 years in Japanese waterways (Matsuguma et al., 2017). A more recent approach to assess the spatial and temporal dynamics of microplastics within sediment is to use agglutinated benthic foraminifera. These marine protists are found globally in sediments and glue the material around them to form their tests (Benito, 2020). These organisms are often used to determine past environmental conditions (Edwards and Horton, 2000), including the presence of microplastics over time (Grefstad, 2019; Langlet et al., 2020; Birarda et al., 2021). Therefore, agglutinated benthic foraminifera can be used to examine the history of microplastic

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https://doi.org/10.1016/j.marpolbul.2024.116090
Received 14 November 2023; Received in revised form 26 January 2024; Accepted 27 January 2024
Available online 4 February 2024

pollution and their fate in previously unstudied marine environments.

The Gulf of Mexico (GOM) receives freshwater discharge from the largest watershed in North America, yet it remains understudied for microplastics. The GOM receives 60 % of its river discharge from the Mississippi River which covers >16 % of North America (Liu et al., 2013). This river system concentrates pollutants such as excess nutrients (Rabotyagov et al., 2020) and microplastics (Scircle, 2020) and deposits them into the GOM. Sediments from shallow environments (i.e., beaches and estuaries) across this basin contained highly variable quantities of microplastics that ranged from 0 to 150 microplastics m^{-2} and 0 to 1940 microplastics kg^{-1}(Wessel et al., 2016; Beckwith and Fuentes, 2018; Yu et al., 2018; Alvarez-Zeferino et al., 2020; Sanchez-Hernandez et al., 2021; Weitzel et al., 2021). Such high spatial variation was attributed to differences in local urbanization (Yu et al., 2018; Tunnell et al., 2020; Sanchez-Hernandez et al., 2021) and the physical characteristics of each site (i.e., wind, tides, currents; Wessel et al., 2016, Alvarez-Zeferino et al., 2020, Sanchez-Hernandez et al., 2021). Importantly, microplastics can be transported from shallow to deep water environments via bottom currents that can result in accumulation in deep-water sediments (Peng et al., 2018; Kane et al., 2020). However, there is little research on these environments in the GOM.

In the present study, we evaluated the spatial and temporal (i.e. time before plastic production versus after plastic production) dynamics of microplastics in deep-water environments of the GOM, by examining foraminifera tests for microplastics. Using agglutinated benthic foraminifera species found in sediment cores, we addressed the following questions: (1) Have microplastics in GOM deep-water environments increased since plastic production began in the 1950s?; (2) Do microplastics decline with distance from the Mississippi River?; (3) How do microplastics vary with water depth?

2. Methods

Sediment cores were collected from the northern GOM aboard the R/V Weatherbird II from 2011 to 2013 as part of the C-IMAGE Consortium (Center for Integrated Modeling and Analysis of Gulf Ecosystems). Cores were collected with an Ocean Instruments MC-800 multicorer (8 cores, 10 cm diameter, up to 70 cm in length) and then frozen (−20 °C) until analysis in the laboratory. The sampling areas included three sites near the Mississippi River discharge (MIS1, MIS2, MIS3; referred to as Mississippi River area) and three further east on the West Florida Shelf (WFS1, WFS2, WFS3; referred to as West Florida Shelf area; Fig. 1). The cores were taken across a range of bottom depths from 72 to 1187 m in the Mississippi River area, and 150-1200 m in the West Florida Shelf area (Table 1). We have assigned core numbers to correspond to their depths (1 s are the shallowest depths, 3 s are the deepest). We chose these sites to examine microplastics across water depths and regions because the pollutant has been shown to be spatially variable (Uddin et al., 2021). Once in the laboratory, sediment cores were sliced with a calibrated threaded-rod extrusion device at 2 and 5 mm intervals (Schwing et al., 2016) and sediment samples were stored in a freezer (-20 °C) until freeze-dried.

We determined the geochronology of each core by measuring excess ^{210}Pb radioisotopes on Series HPGe (high-purity Germanium) Coaxial Planer Photon Detectors (Brooks et al., 2015; Schwing et al., 2017; Larson et al., 2018). We measured total ^{210}Pb (46.5 Kev), ^{214}Pb (295 Kev and 351 Kev), and ^{214}Bi (609 Kev) to determine activities and reported as disintegrations per minute per gram (dpm g^{-1}) (Brooks et al., 2015). Supported ^{210}Pb in situ, was determined by averaging the activities of ^{214}Pb (295 Kev and 351 Kev) and ^{214}Bi (609 Kev) as a proxy for ^{226}Ra (Brooks et al., 2015; Schwing et al., 2017). Then, we subtracted the supported ^{210}Pb from the total ^{210}Pb to give the excess ^{210}Pb, which we used to date the most recent ~100 years of the core (Table 2; Brooks et al., 2015, Schwing et al., 2017). Both Constant Initial Concentration

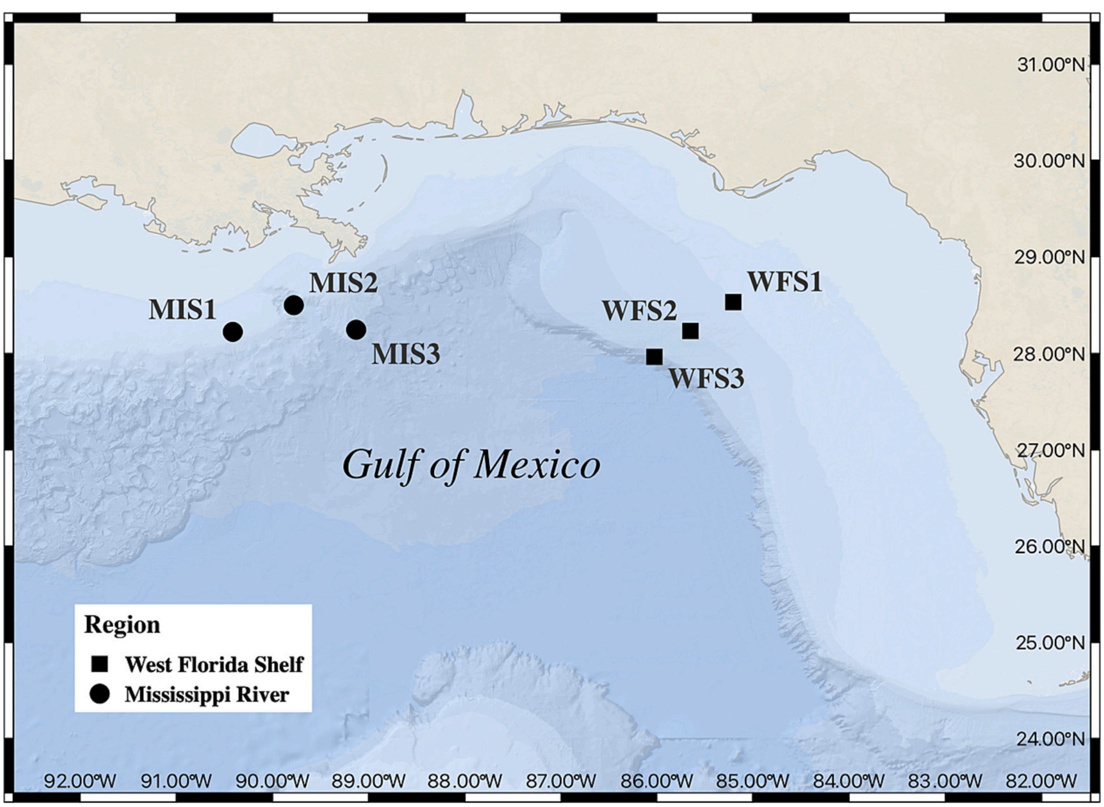

Fig. 1. Map of locations where sediment cores were sampled. Sediment cores are indicated by the squares and circles. Circles are the Mississippi River cores and squares are the West Florida Shelf cores.

Table 1
Descriptions of the sites and diversity indices for each core. NA indicates data were unavailable.

Core	Water depth (m)	Distance to coast (km)	Name of nearest river	Distance to nearest river (km)	Name of nearest port	Distance to nearest port (km)	Name of nearest tourist beach	Distance to nearest tourist beach (km)	Fisher's alpha	Equitability J	Shannon
MIS1	72	91	Mississippi	154	Port Fourchon	100	Grand Isle Beach	1148	16.35	0.91	3.55
MIS2	550	54	Mississippi	92	Port Fourchon	78	Grand Isle Beach	81	6.64	0.76	2.46
MIS3	1187	77	Mississippi	103	Port Fourchon	142	Grand Isle Beach	138	11.21	0.84	3.00
WFS1	150	116	Apalachicola	135	Port St. Joe	148	St. George Island	128	NA	NA	NA
WFS2	400	159	Apalachicola	180	Port St. Joe	181	St. George Island	174	NA	NA	NA
WFS3	1200	198	Apalachicola	220	Port St. Joe	219	St. Joseph Peninsula	213	6.50	0.54	1.81

Table 2
Year and uncertainty assigned to each depth interval within each core.

Core	Depth interval (mm)	Age ± uncertainty (years)
MIS1	0–2	2014 ± 2.22
	2–4	2013 ± 2.22
	4–6	2013 ± 2.22
	6–8	2013 ± 2.22
	8–10	2013 ± 2.22
	90–95	1998 ± 2.40
	95–100	1997 ± 2.42
	220–225	1967 ± 3.14
	390–400	1901 ± 4.13
MIS2	0–2	2013 ± 1.28
	50–55	2008 ± 1.28
	95–100	2003 ± 1.30
	215–220	1965 ± 1.86
	280–285	1943 ± 2.48
	310–315	1933 ± 2.76
	395–400	1907 ± 3.53
MIS3	0–2	2012 ± 1.47
	2–4	2012 ± 1.47
	4–6	2011 ± 1.47
	6–8	2010 ± 1.48
	8–10	2010 ± 1.48
	100–105	1966 ± 1.94
	105–110	1962 ± 2.00
	130–135	1946 ± 2.40
	190–195	<1900
	195–200	<1900
WFS1	0–2	2011 ± 2.83
	2–4	2011 ± 2.84
	14–16	2006 ± 2.87
	105–110	1955 ± 3.17
	115–120	1943 ± 3.23
	130–135	1904 ± 3.32
	190–195	<1900
WFS2	0–2	2011 ± 2.91
	4–6	2009 ± 2.94
	16–18	1998 ± 3.24
	60–65	1922 ± 17.64
	105–110	<1900
	190–195	<1900
WFS3	0–2	2011 ± 2.22
	2–4	2010 ± 2.23
	10–12	2005 ± 2.31
	100–105	1938 ± 4.62
	110–115	1932 ± 4.79
	190–195	<1900

(CIC) and Constant Rate of Supply (CRS) models were applied to assign specific ages to each data point in the core. The CRS model yielded the most reasonable results, likely because of variable sediment accumulation rates (Appleby and Oldfieldz, 1983; Binford, 1990; Brooks et al., 2015).

We isolated the foraminifera from sediment samples (at different depth intervals in the cores) that corresponded with time periods that dated before and after plastic production began in the 1950s. The total number of foraminifera were not counted because of the high number of foraminifera, however, the foraminifera samples were weighed to standardize the data. Foraminifera samples (i.e. a collection of individual foraminifera taken from a sediment sample) from depth intervals dated before 1950 were expected to have no microplastics and therefore served as controls in our study. The sediment samples across sites were not from the same depth-intervals within the cores due to differences in sediment accumulation rates at each site. We washed selected sediment samples with a sodium hexametaphosphate solution to remove sediment and terrestrial particles from foraminiferal tests. Then, we dried the foraminifera samples and stored them at room temperature. We only considered agglutinated foraminifera because they cement particles together to form their tests (Bender and Hemleben, 1988) and at the time of our study there was not yet evidence that calcareous foraminifera could incorporate plastic particles into their test (Erez, 2003; Joppien et al., 2022). The use of agglutinated foraminifera to assess microplastics in sediments ensured no secondary contamination after collection because particle incorporation into their tests required the organisms to be alive.

We stained the foraminifera with Nile Red to identify microplastics contained within the tests (Shim et al., 2016; Maes et al., 2017). The foraminifera samples here have been washed to remove sediment and other particles so only the foraminifera remain. We immersed the foraminifera samples in Nile Red (5 mg L^{-1} acetone) for 30 min, then poured them over a glass fiber filter and dried them in an oven at 60 °C for 12 h (Shim et al., 2016, Maes et al., 2017). After the foraminifera were completely dried, we weighed (Veritas, H&C weighing systems, M214A and Mettler-Toledo MT5) each foraminifera sample to determine total weight of foraminifera (g) and sorted them through a series of metal sieves into three size classes (63- < 150 μm, 150- < 300 μm, 300–5000 μm; Schwing et al., 2018). We used a stereomicroscope (Amscope SF-2TRA, 10-30× magnification) with cyan (490–515 nm wavelength) LED lights, and an orange filter to count the stained microplastics within the agglutinated foraminifera tests. The fluorescent light illuminated the microplastics that were stained with the Nile Red dye. The orange filter was used to transmit the fluorescence so only the stained microplastics fluoresce. The microplastics fluoresced a bright orange color and were easily identified. We examined the entire foraminifera sample, when possible, but if it was too large, we analyzed and weighed a portion of it (minimum of 30 % of the sieve fraction). When we found foraminifera that contained microplastics, we separated them from the rest of the foraminifera sample to be identified. We also counted foraminifera tests that were damaged because some species, such as *Saccorhiza ramosa* (Brady, 1879) and *Archimerismus subnodosus* (Brady, 1884), break easily. We determined the number of foraminifera that contained microplastics in each foraminifera sample as well as the number of microplastics within each test (microplastic counts) and per weight of foraminifera (microplastic counts g^{-1} foraminifera), and the relative number of microplastics in each site per period analyzed (% microplastic counts). We only counted microplastics that were completely incorporated into the test. We identified the foraminifera to the lowest taxonomic level possible (genus or species; https://www.marinespecies.org/). Then, we took photographs of the foraminifera that contained microplastics with a Canon EOS 2000D camera connected to a stereomicroscope (Nikon SMZ800N with Nikon LV-TV adapter).

We used a geographic information system (GIS) to determine the distance of each site to the nearest coast, river, port, and tourist beach since they have been shown to be sources of microplastics to the ocean (Scircle, 2020; Masia et al., 2021). Distance from land features was higher with increasing depth for WFS sites but not MIS sites. Among the sites in the West Florida Shelf area WFS1 was the closest of cores to the coast (115.8 km), nearest river (134.7 km), port (147.5 km), and beach (127.6 km), and WFS3 was the farthest (198 km, 220.3 km, 219.4 km, 213.2 km, respectively; Table 1). Among sites in the Mississippi River area, MIS2 was the closest to the coast (54.1 km) and nearest river (91.9 km), and MIS1 was the farthest (91.1 km and 154.2 km, respectively; Table 1). Additionally, MIS2 was the closest to the nearest port (77.7 km) and beach (81.3 km) and MIS3 was the farthest of the Mississippi River cores (141.9 km and 137.6 km, respectively; Table 1). Importantly, all the Mississippi River cores were closer to the coast than the West Florida Shelf cores (Table 1). Also, we examined the potential effect of sediment accumulation rates on microplastic counts among the studied sites by plotting microplastics g^{-1} foraminifera against sediment accumulation rates to determine if there was a relationship.

To assess potential effects of microplastics on foraminifera communities, we used diversity indices (Fisher's alpha, Equitability J, and Shannon's diversity index) that were previously published for WFS3, MIS1, MIS2, and MIS3 (Table 1; Romero et al., 2016, Schwing et al., 2018); these data were not available for WFS1 and WFS2. Diversity was calculated across all foraminifera regardless of microplastic presence. Diversity was variable but tended to be higher in the cores taken further from the Mississippi River cores (Table 1). Diversity for WFS3 was low compared to MIS3 and MIS1 (Table 1).

To examine the effects of water depth (fixed effect; i.e. across all observations, this variable is assumed to be constant), time (fixed effect; pre-plastic production (≤ 1950) = 0, post-plastic production (>1950) = 1), and region (fixed effect; Mississippi = MS, West Florida Shelf = WFS) on microplastic abundance (response), we performed a generalized linear mixed model (GLMM) with core as a random effect to account for multiple measurements. We performed all analyses in R (R Development Core Team, 2022), with package glmmTMB (Brooks et al., 2017) for the GLMM and the DHARMa package (Hartig and Hartig, 2021) for residual diagnostics. We used Akaike information criterion (AIC) to determine the best model then tested for diagnostics to ensure the appropriateness of it. We determined the microplastic response data were zero-inflated so we assessed models that can handle large amounts of zeros (Zuur et al., 2009). The model with the best AIC was a zero-inflated negative binomial model with region and water depth as effects in the conditional model, and time as an effect in the zero-inflation model (AIC = 288.3). We removed time as an effect in the conditional model after we determined its contribution was not significant ($p > 0.05$).

3. Results

All the microplastics observed in the foraminifera tests were visually determined to be round to elongated fragments and relatively easy to detect (Fig. 2). The arrows in Fig. 2 point to the microplastics. The microplastics illuminated a bright orange and were easy to detect. Most of the microplastics (78 %) we observed were in the largest size range of foraminifera (300–5000 μm), followed by the 150- < 300 μm (20 %), and 63- < 150 μm (2 %) sizes (Fig. 3).

We found a total of 92 microplastics in 53 foraminifera tests from 10 identified species (Fig. 4). Only two tests contained microplastics that we were not able to identify (denoted as "unknown species"). The most common foraminifera species with microplastics was *Saccorhiza ramosa*

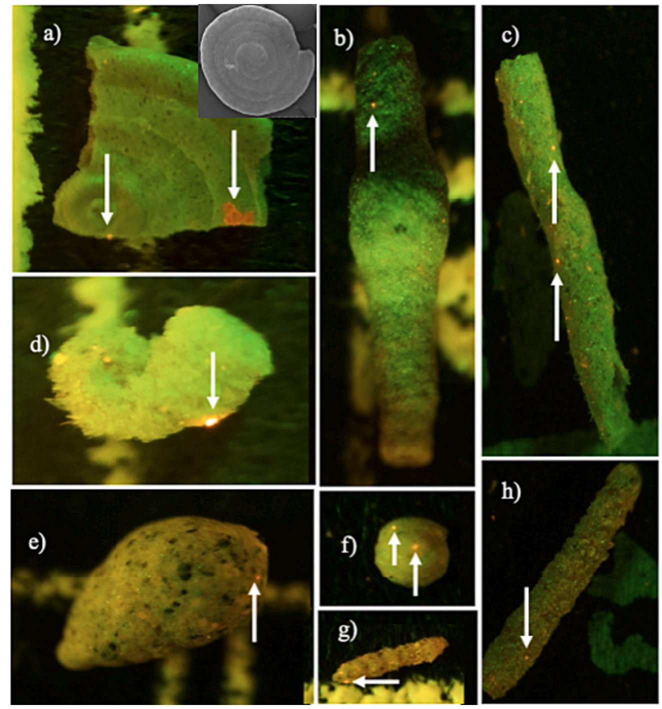

Fig. 2. Images of fluorescing microplastics incorporated into foraminifera: a) Ammodiscus tenuis (inset image of specimen with no microplastics), b) Archimerismus subnodosus, c) *Saccorhiza ramosa*, d) Ammobaculites spp., e) Hippocrepina spp., f) *Trochammina squamata*, g) *Bigenerina nodosaria*, and h) *Hyperammina friabilis*.

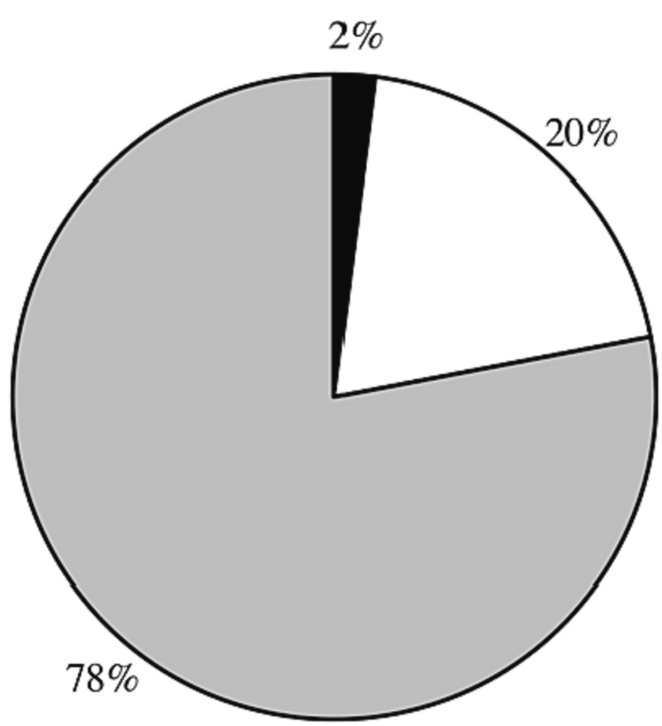

Fig. 3. Size classes of foraminifera that had microplastics incorporated into their tests for all cores. 63–<150 μm (black), 150–<300 μm (white), 300–5000 μm (gray).

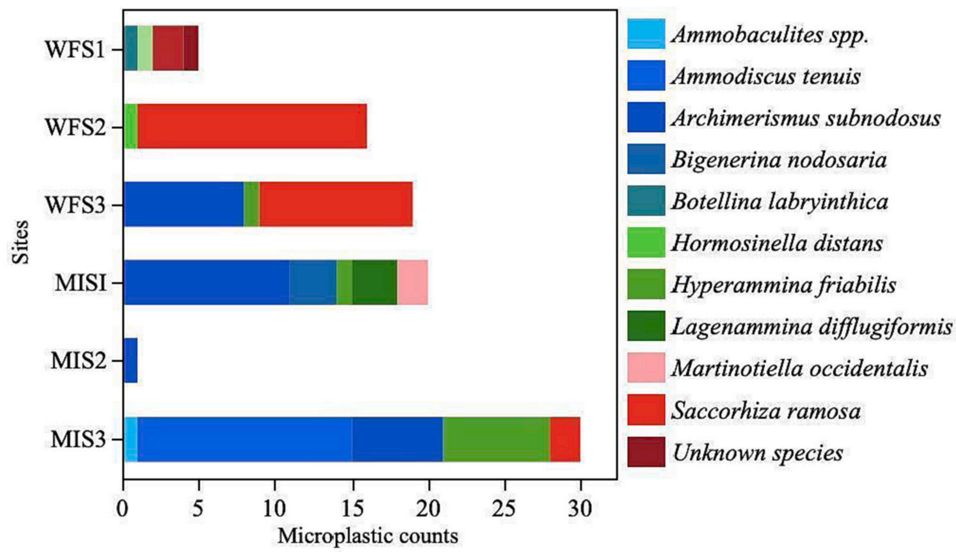

Fig. 4. Microplastic counts for all species at each station studied. Two tests containing microplastics were not able to be identified and were denoted as unknown species.

(Brady, 1879; Total: 14 observed to include microplastics), mostly in the West Florida Shelf area, and *Archimerismus subnodosus* (Brady, 1884; Total: 16 observed to include microplastics), mostly found in the Mississippi River area. The Mississippi River area had the highest number of microplastics in site MIS3 (30 microplastics; Fig. 4). Also, for the Mississippi River area, we observed the lowest number of microplastics and number of species in site MIS2 (one species with one fragment).

As expected, the number of foraminifera with microplastics was higher after plastic production began in the 1950s throughout all cores (Fig. 5a). A similar trend was found for microplastic counts g^{-1} of foraminifera (Fig. 5b) and percentage microplastic counts g^{-1} foraminifera (Fig. 6). However, microplastics were found pre-plastic production in one core (WFS1; 190–195 mm; <1900), but these represented a very low proportion of the total microplastics observed across all cores (0.03). Microplastics from <1900–2013 ranged from 0 to 32 microplastics g^{-1} of foraminifera in the West Florida Shelf cores and 0–65,000 microplastics g^{-1} of foraminifera in the Mississippi River cores. We also did not find a relationship between sediment accumulation rates and microplastic counts.

The probability of a foraminifera sample without microplastic presence (i.e., zero count) was lower for those from post-plastic production compared to pre-plastic production ($z = -3.04$, $p < 0.01$, Table 3). Additionally, microplastics were higher in the Mississippi River area ($z = 4.04$, $p < 0.01$, Fig. 7) and in deeper waters (>500 m depth; $z = 5.89$, $p < 0.01$, Fig. 8).

4. Discussion

This study was among the first to assess the temporal dynamics of microplastics in the GOM. Using agglutinated foraminifera in sediment cores from the northern GOM, we found a significantly higher number of microplastics following the beginning of the plastic production circa the 1950s. Most microplastics were observed in recent sediments that were deposited after 2000. We also observed spatial variation in microplastic presence and abundance. Sites in the Mississippi River area had microplastic abundances several orders of magnitude higher than those in the West Florida Shelf area. In addition, we observed higher microplastic abundances in deep sites as well as those closest to land and associated features that are common sources for this pollutant. These results highlight the complexities and variation in microplastic distribution in oceanic environments. Future work is needed in addition to this study to further discern large scale processes since the time and effort to collect

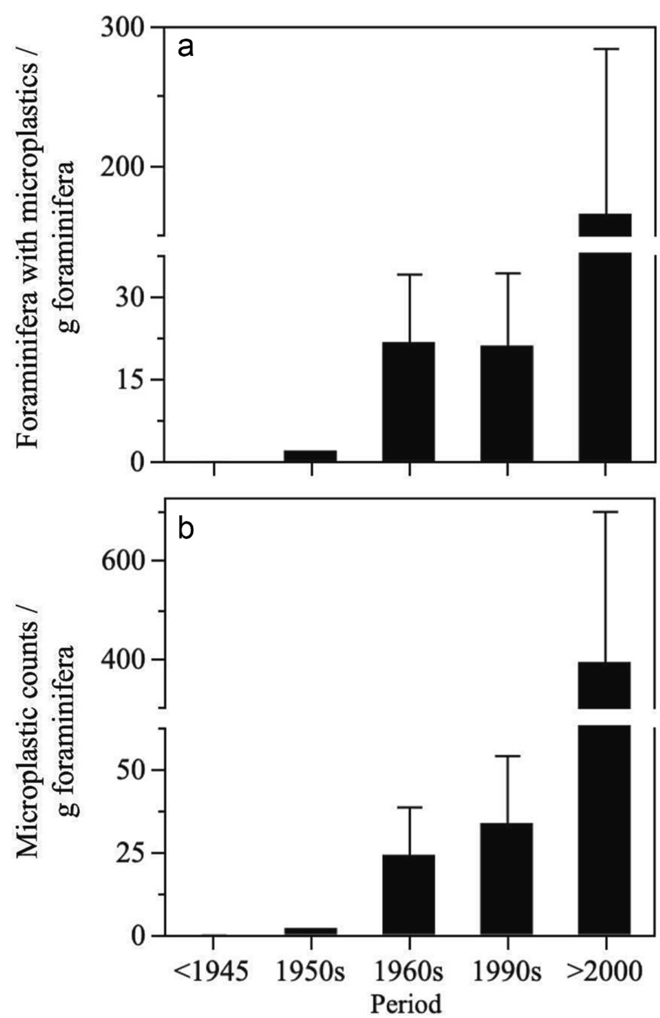

Fig. 5. The number of foraminifera with microplastics (a) and total number of microplastics (b) per year with a focus on time periods with microplastics (>1950).

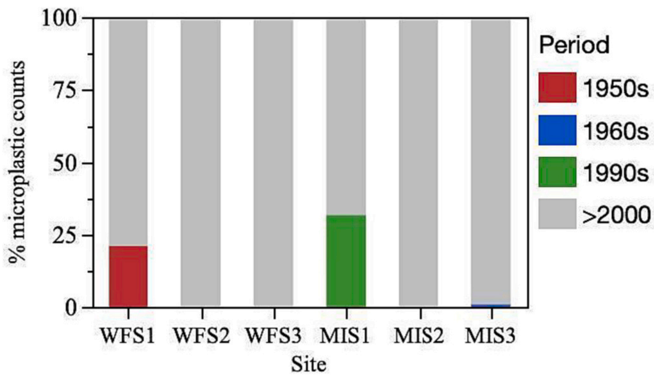

Fig. 6. Relative number of microplastics found in each site per period analyzed (% microplastic counts). Pre-plastic production (1900–1945) is not included because foraminifera with microplastics were not found during this time.

Table 3
Output of GLMM to evaluate the effects of region (Mississippi = regionMS), time (post-plastic production = group1), and water depth on microplastics g^{-1} of foraminifera incorporated in agglutinated foraminifera tests (α = 0.05, $\boldsymbol{p} < \mathbf{0.05}$). The West Florida Shelf region and pre-plastic production time were used as model reference.

	Estimate	Std. error	z value	Pr(>|z|)
Conditional model				
Intercept	0.396	0.648	0.612	0.541
regionMS	3.454	0.856	4.035	**0.000**
water depth	0.004	0.001	5.889	**0.000**
Zero-inflation model				
Intercept	2.483	1.055	2.354	**0.019**
group1	−3.689	1.212	−3.043	**0.002**

Random effects	Variance	Std. Dev.
Core	7.188e−09	8.478e−05

and assess marine sediment cores can be large.

Microplastics were higher post-plastic production in sediment cores collected from the northern GOM. This was expected because microplastic pollution has been shown to increase over time, largely tracking plastic production (Hale et al., 2020). This pattern has been well documented globally from coastal to offshore sediments (Claessens et al., 2011; Matsuguma et al., 2017; Yao et al., 2019; Courtene-Jones et al., 2020; Uddin et al., 2021). However, microplastics in sediments without a temporal trend were found in Tokyo Bay due to rapid sedimentation or sediment disturbance (Matsuguma et al., 2017). Likewise, one core in our study exhibited a different trend than the others because microplastics were found in depths corresponding to the time period before plastic production began. In this core, this was likely due to mixing of foraminifera from shallow core depths to deeper sediment layers during extrusion, but this was not enough to affect the geochronology of the core. Martin et al. (2022) reviewed literature on the temporal dynamics of microplastics in sediments and reported that several studies found the pollutant before plastic production began. This was attributed to either reworked sediments (e.g., bioturbation, pore water transport) or procedural contamination (Martin et al., 2022). Although it is important to minimize contamination, it can be difficult due to the small size of the microplastics and foraminifera. The contamination from the mixing of foraminifera from different sediment layers only occurred in one core but has revealed the need to take more precautions during the extrusion process.

Microplastics also exhibited spatial variability as evidenced by differences between the two areas studied and across water depths. Although they are known to vary spatially in shallow environments in the GOM, microplastics have been previously unstudied in the deeper sediments of the shelf slopes in this basin. Our study was the first to quantify microplastic distributions in shelf to slope depth sediments in the GOM. The differences between the two focal regions highlight the high levels of spatial variability microplastics can exhibit. The GOM receives a large amount of riverine input (1100 km^3 yr^{-1}), of which roughly 655 km^3 yr^{-1} originates from the Mississippi River alone (Liu et al., 2013). Scircle (2020) estimated there were 87 to 129 trillion microplastics per day near the mouth of the Mississippi River. Thus, the higher amount of microplastics we observed in the Mississippi River area may be attributed to the large amount of the pollutant that is carried by this river system. Similar distribution patterns have been reported in other areas. For example, Falahudin et al. (2020) also found microplastics in Indonesian bays decreased further from the mouth of a river. Surface water transport such as eddies or the Gulf Loop Current could affect microplastic transport and deposition to these sites and the Desoto Canyon and other geomorphological characteristics could affect microplastic accumulation (Brooks et al., 2015; Romero et al., 2016; Schwing et al., 2017). Additionally, the West Florida Shelf area is located further from the coast which may have contributed to the differences between the studied areas. Indeed, several studies have reported microplastics decrease with increased distance from the coast and attributed this to being further from pollution sources (Graca et al., 2017; B. Zhang et al., 2019; C. Zhang et al., 2019; D'Hont et al., 2021). Our study supports previous work that has found sites nearer to sources of pollution (e.g., rivers, coastlines) have greater abundances of microplastics (Yu et al., 2018; Tunnell et al., 2020; Sanchez-Hernandez et al., 2021).

We found that microplastics were higher in deeper waters in the GOM, however there was greater uncertainty at these depths. Microplastic abundance can be higher in deeper waters because of oceanographic processes and features such as bottom currents, erosion, grain size, or resuspension events (Kane et al., 2020; Lechthaler et al., 2021; Sun et al., 2021). This is supported by a study that found microplastic ingestion in fish and crustaceans was higher in deeper water depths in the GOM (Bos et al., 2023). In contrast, others have found microplastics decrease with water depth due to increased distance from the coast and pollution sources (D'Hont et al., 2021; Manbohi et al., 2021; Uddin et al., 2021). However, we found that microplastics were lower at sites that were further from the coast, but they were higher in deeper waters. This indicates other process(es), such as bottom currents, in the GOM transported microplastics to these deep-water depths (Hamilton and Lugo-Fernandez, 2001). However, due to the high uncertainty associated with our results, it is still unclear how microplastics vary with water depth in the GOM. It is also important to consider the exact environmental conditions at the seafloor and the ecological characteristics of each species were not considered for this paper. Additional research is needed to better understand microplastic distribution in sediments and how oceanographic processes affect it.

Little is known about microplastic incorporation into foraminifera tests; however, our study contributes new information on this topic. Based on our results, foraminifera in the largest size range were found to incorporate more microplastics into their tests, specifically the 300–5000 μm and 150- < 300 μm sizes (Fig. 3). These sizes of foraminifera may be more likely to encounter microplastics due to their greater surface area. However, our hypothesis has not been examined, to our knowledge. Grefstad (2019) found that fewer agglutinated foraminifera were observed to ingest the plastic compared to calcareous species. Perhaps this is further evidence that agglutinated foraminifera do not seek interactions with microplastics. Microplastic characteristics, organisms' behavior, morphology, and physiology could influence microplastic incorporation into foraminiferal tests but discerning these mechanisms was beyond the scope of this study (Au et al., 2017;

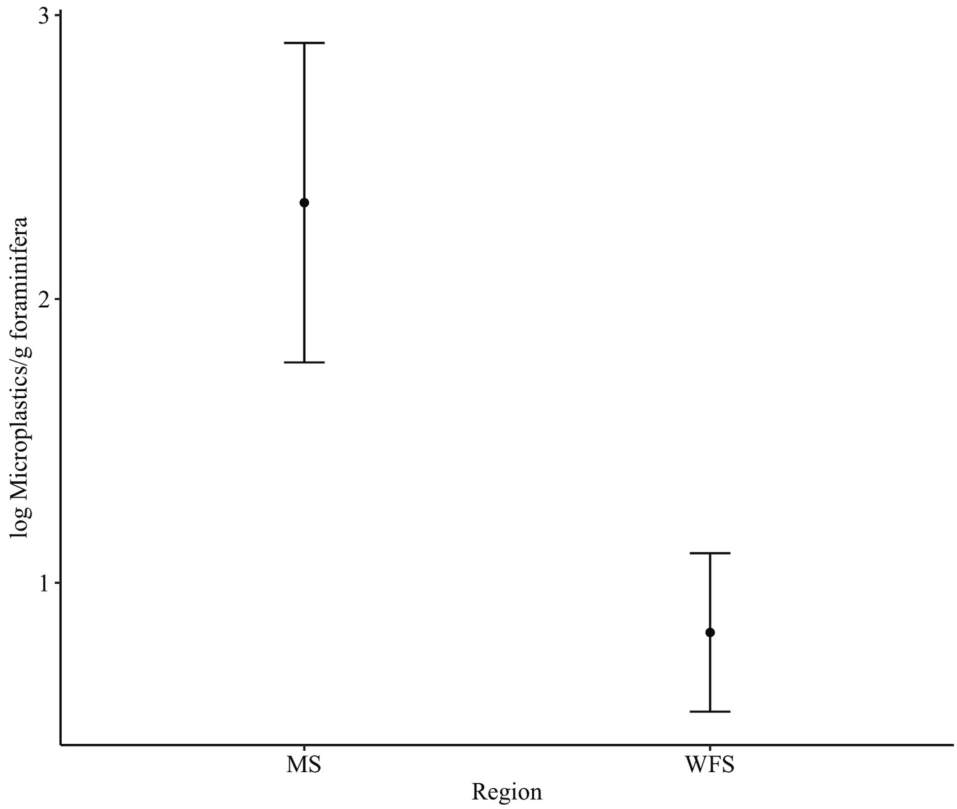

Fig. 7. Log transformed microplastics g-1 of foraminifera for each region. MS is the Mississippi River region and WFS is the West Florida Shelf region. Circles are the mean and whiskers are one standard error.

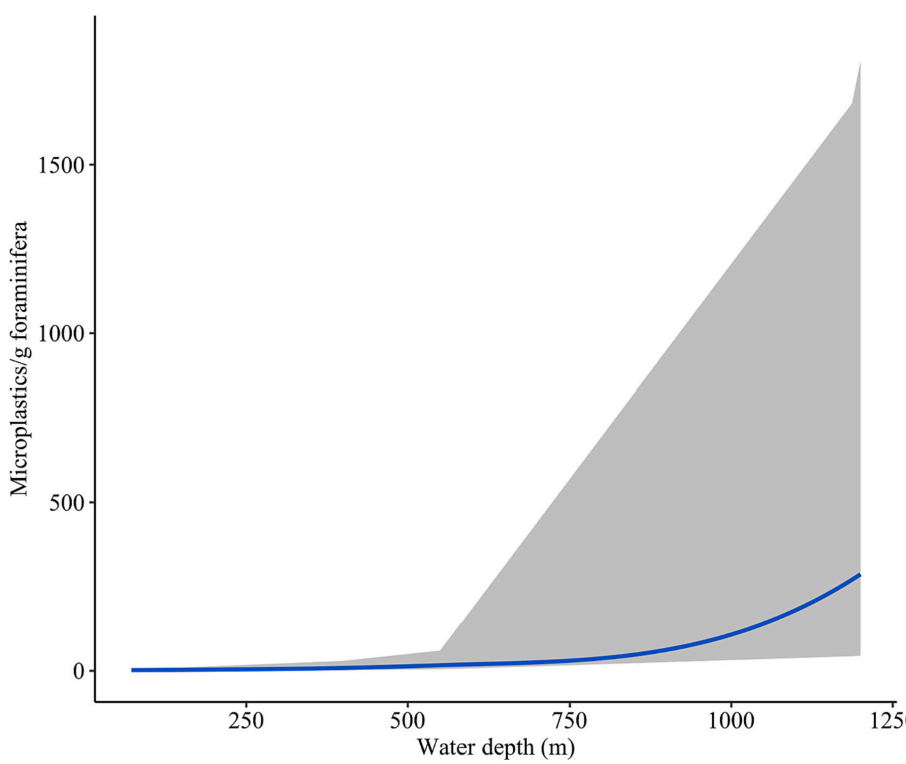

Fig. 8. Modelled effect of water depth on microplastics g^{-1} of foraminifera.

Grefstad, 2019). More research is needed to determine whether some species selectively incorporate the pollutant into their tests and how this could affect them.

The diversity indices lend some information about the condition of the benthic foraminiferal communities and their response to anthropogenic activity. Diversity was higher for the Mississippi River area compared to that from the West Florida Shelf. Within the Mississippi River area, diversity was higher with increased distance from both the coast and river. This indicates foraminiferal communities closer to the coast and river were less diverse. While this cannot definitively be concluded based on our study, they may have been affected by their proximity to anthropogenic activities and plastic pollution inputs, although there could also be other causes for low diversity. Indeed, one study found that microplastics can leach chemicals into foraminifera, weaken their tests, and induce oxidative stress (Birarda et al., 2021). In contrast, WFS3 was the site farthest from the coast, and it had low diversity indices compared to the Mississippi River area. The foraminiferal community at this site could have been affected by other factors that were outside the scope of this study, such as oxygen concentration, grain size, and concentration of total organic carbon (Bouchet et al., 2012).

5. Conclusions

Microplastics are a global, ubiquitous pollutant. This study was the first to examine microplastics in deep-water sediments of the GOM, but it also highlights the need for further research. We found that microplastics were higher post plastic production and closer to the Mississippi River. Additional foraminifera samples at locations across the GOM would help to further identify the distribution, abundance, and spatial variability of microplastics in this large marine basin and to resolve whether these six cores accurately represent the conditions of the larger area. Further work can also examine the relative contributions of microplastics to the GOM from other rivers. We also found that microplastics were higher in deeper waters, but more work is needed to understand this distribution in the GOM, since uncertainty was high. Additionally, microplastics were found in larger foraminifera but did not appear to be selectively incorporated into their tests. However, there is little research on this topic so more work is needed to assess the interactions between agglutinated foraminifera and microplastics. Finally, the effects of microplastics on organisms are complex and can range from negative to positive, or have no effect (Plafcan and Stallings, 2022). Future work should assess the effects of microplastics on foraminifera since this is an emerging field. Additionally, the microplastics from this study could be further assessed in future work to identify the plastic types that were incorporated into the foraminifera. It is important to assess the risk of microplastics across the globe, and our study was the first to evaluate this pollutant in deep-water sediment in the GOM.

CRediT authorship contribution statement

Martina M. Plafcan: Conceptualization, Data curation, Formal analysis, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing. **Patrick T. Schwing:** Conceptualization, Investigation, Methodology, Resources, Supervision, Writing – review & editing. **Isabel C. Romero:** Data curation, Formal analysis, Visualization, Writing – review & editing. **Gregg R. Brooks:** Data curation, Formal analysis, Writing – review & editing. **Rebekka A. Larson:** Data curation, Formal analysis, Writing – review & editing. **Bryan J. O'Malley:** Data curation, Formal analysis, Investigation, Writing – review & editing. **Christopher D. Stallings:** Conceptualization, Formal analysis, Project administration, Supervision, Writing – review & editing, Investigation, Methodology, Resources, Visualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Martina M. Plafcan reports financial support was provided by Fish Florida! Scholarship. Patrick T. Schwing reports financial support was provided by Gulf of Mexico Research Initiative, Center for Integrated Modeling and Analysis of Gulf Ecosystems. Isabel C. Romero reports financial support was provided by Gulf of Mexico Research Initiative, Center for Integrated Modeling and Analysis of Gulf Ecosystems. Gregg R. Brooks reports financial support was provided by Gulf of Mexico Research Initiative, Center for Integrated Modeling and Analysis of Gulf Ecosystems. Rebekka A. Larson reports financial support was provided by Gulf of Mexico Research Initiative, Center for Integrated Modeling and Analysis of Gulf Ecosystems. Bryan J. OMalley reports financial support was provided by Gulf of Mexico Research Initiative, Center for Integrated Modeling and Analysis of Gulf Ecosystems.

Data availability

Data will be made available on request.

Acknowledgments

We thank Tristan Lam for his help in preparing the samples and Dr. Nicole Fogarty for input on early versions of this manuscript. The authors thank the crew of the *R/V Weatherbird II* for their assistance during the field program. Radioisotope and benthic foraminifera assemblage data are publicly available through the Gulf of Mexico Research Initiative Information & Data Cooperative (GRIIDC) at http://data.gulfresearchinitiative.org.

Funding

This work was supported by the Anne & Werner Von Rosenstiel Fellowship, the Linton Tibbetts Endowed Graduate Student Fellowship, the Fish Florida Scholarship, and the University of South Florida's College of Marine Science. This research was made possible in part by a grant from the Gulf of Mexico Research Initiative, Center for Integrated Modeling and Analysis of Gulf Ecosystems (C-IMAGE).

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