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Abstract:

Anthropogenic debris has been reported in all studied marine environments, including the deepest parts of the sea. Finding areas of accumulation and methods of transport for debris is important to determine potential impacts on marine life. This study analyzed both sediment cores and Remotely Operated Vehicle video from Norfolk Canyon, and Remotely Operated Vehicle video from Baltimore Canyon to determine the density and distribution of debris, including both micro- and macroplastics. The average microplastic density in Norfolk Canyon sediment was 37.30 plastic particles m^{-2} within the canyon and 21.03 particles m^{-2} on the adjacent slope. In video transects from both Norfolk and Baltimore canyons, the largest amounts of macroplastic were recorded near the canyon heads. Our findings contribute to a growing evidence base that canyons and their associated benthic invertebrate communities are important repositories and conduits for debris to the deep sea.

Keywords:

Plastic, microplastic, deep sea, sediment, ROV, pollution transport.

Introduction:

Submarine canyons are important hotspots of deep-sea biodiversity (CSA et al., 2017; De Leo et al., 2010). Canyons connect continental shelves and the deep sea and are known to be active conduits of sediment, water masses, and larvae (Bennet, 1984; Mordecai et al., 2011). However, along with essential organic materials, canyons can transport marine litter and other pollutants by funneling currents (Azaroff et al., 2020; Galgani et al., 2000; Masson et al., 2010; Zhong and Peng, 2021). It is important to identify and study where and how debris is deposited in the deep sea to more fully understand how litter behaves in the ocean and which marine communities might be most at risk.

Recent calculations estimate there may currently be as many as 5.25 trillion plastic particles afloat in the ocean (Eriksen et al., 2014). Of these 5.25 trillion particles, three types of plastic polymers (polyethylene, polypropylene, and polystyrene) comprise a mass of 11.6-21.1 million tons (Pabortsava and Lampitt, 2020). These figures are still likely underestimates, since about 4.8 to 12.7 million metric tons of plastic may enter the ocean from land each year (Jambeck et al., 2015). Furthermore, it is estimated that about 20% of marine debris originates from offshore litter sources such as fishing and shipping, though this number can vary (Liubartseva et al., 2018). This difference between estimates of plastics entering the ocean from either terrestrial or offshore sources and plastics floating in the ocean has led to a search for sinks (Long et al., 2015).

The deep sea seems to be such a sink for plastics (Courtene-Jones et al., 2017; (Naranjo-Elizondo and Cortés, 2018); Peng et al., 2020; Van den Beld et al., 2017; Williams et al., 2005; Woodall et al., 2014). Several mechanisms have been identified by which plastics might reach the deep ocean floor. Plastic polymers, some of which are positively buoyant and float on the surface of the ocean, can become weighed down by biofouling, causing them to sink (Barnes et al., 2009; Mordecai et al., 2011; Ye and Andrady, 1991). Debris can also sink as a result of "plastic fallout," where debris is fragmented and sinks in the water column in smaller particles (Egger et al., 2020). In fact, it is estimated that 70% of plastic in the ocean eventually sinks to the seafloor (Pham et al., 2014). Microplastics (plastic particles 0.33-5.0 mm in diameter) ingested by marine organisms can be incorporated into their feces and subsequently transported to the seafloor (Courtene-Jones et al., 2017; Eriksen et al. 2014; Coppock et al. 2017). Microplastics can also sink with settling detritus from the surface, since phytoplankton aggregates incorporate and concentrate small debris (Long et al., 2015). Once litter sinks, it may accumulate on geologically structured areas such as reefs, seamounts, hadal trenches, and canyons and may persist for over 500 years on the sea floor due to the absence of thermal oxidation and solar radiation (Barnes et al., 2009; Derraik, 2002; Van den Beld et al., 2017). However, sinking is not the only process that influences dispersal of plastics on the seafloor; sedimentary gravity flows, thermohaline-driven currents, and deep ocean circulation are known to transport and accumulate debris (Kane et al. 2020; Pabortsava and Lampitt, 2020; Pierdomenico et al. 2019; Pierdomenico et al. 2020).

Deep-sea studies using Remotely Operated Vehicle (ROV) or submersible techniques (e.g., video), bottom trawl nets, or sonar show that large debris is ubiquitous in the deep sea (Amon et al., 2020; Barboza et al., 2019; Ramirez et al., 2013; Spengler and Costa, 2008). Debris in the ocean can accumulate in areas of high sedimentation such as canyons, and the presence of large anthropogenic debris in submarine canyons has been well-documented (Dominguez-Carrió et al., 2020; Mordecai et al., 2011; Schlining et al., 2013; Van den Beld et al., 2017). However, these studies do not include microplastics, which are too small to resolve with video or to catch with large trawl nets. Recently microplastics were found by sediment analysis in all studied deep-sea environments, even the deepest abyssal trenches (Fischer et al., 2015; Peng et al., 2018; Sanchez-Vidal et al., 2018; Van Cauwenberghe et al., 2013). Two papers to date have identified the presence of small synthetic microfibers in submarine canyons (Sanchez-Vidal et al., 2018; Woodall et al., 2014).

This study is one of the first to conduct sedimentary microplastic analysis solely focused on submarine canyons. We combined the sampling approaches of sediment cores and ROV video to conduct a more complete study of anthropogenic litter of all sizes in two submarine canyons. We analyzed coring data from within Norfolk Canyon and the adjacent continental slope to quantify smaller anthropogenic debris and microplastics in the sediment and to compare the canyon interior to the open slope. We compared ROV video data from Norfolk Canyon and Baltimore Canyon to quantify larger anthropogenic debris within the canyon environments and to determine whether distributions of larger debris vary as a function of depth or canyon. We hypothesized that strong down-canyon currents might concentrate microplastics within Norfolk Canyon, yielding higher densities within the canyon than on adjacent slope areas. We also hypothesized that larger debris in both Baltimore and Norfolk Canyons might accumulate near the canyon heads, due to hard substrates present in the higher and middle reaches of the canyons (CSA et al., 2017). These hypotheses build on a growing recognition that submarine currents play an important role in the transport and dispersal of debris in the deep sea (Kane and Fildani, 2021; Pierdomenico et al., 2020; Pohl et al., 2020).

Norfolk Canyon and Baltimore Canyon are two well-studied canyons along the middle Atlantic continental margin of the United States (CSA et al., 2017; Ross et al., 2015). These shelf-incising canyons are located on the Mid-Atlantic Bight (MAB), which extends over 500 km of the continental slope and shelf from Cape Cod to Cape Hatteras (CSA et al., 2017; Harris and Whiteway, 2011). The two canyons, approximately 75 km apart, are cut 31 km (Baltimore Canyon) and 25 km (Norfolk Canyon) into the MAB shelf (CSA et al., 2017; Obelcz et al. 2014). Sediment within the canyons consists primarily of silt and clay and can be dynamically transported due to near-bottom currents (Csanady et al., 1988; Forde, 1981; Keller and Shepard, 1978). Surface water movements near both canyons are dominated by the Slope Sea Gyre and generally flow to the southwest (CSA et al., 2017). Within the canyons, flow is primarily driven by tidal activity, internal waves, and the periodic gravity and current-induced turbidity current (Keller and Shepard, 1978; Obelcz et al. 2014). Turbidity due to currents is much higher within the canyons than on the adjacent continental slopes, leading to dense nephloid layers in the middle of both canyons (CSA et al., 2017; Ross et al., 2015). Baltimore and Norfolk canyon currents move downslope in the upper reaches of the canyons, suggesting a mechanism for sediment transport through the deepest parts of the canyons to the abyssal plain (CSA et al., 2017).

Canyons of the Mid-Atlantic Bight contain unique habitats with high productivity and diversity (CSA et al., 2017). These habitats support active recreational and commercial fishing, the primary human use in and around the canyons (Racanelli, 2016). Furthermore, as marine areas that straddle the shelf and slope in a region of high human activity, they are also vulnerable to anthropogenic disturbances. Baltimore and Norfolk canyons are both located above 1500 m depth, rendering them more vulnerable to disturbance from fishing practices such as bottom trawling than deeper canyons (Harris and Whiteway, 2011). Baltimore Canyon was formed millions of years ago by a channel that is now the Delaware River, connecting the canyon to a potential riverine source of pollution (Racanelli, 2016). The Delaware River is one of the top 1000 most polluting rivers in the world and the most polluting river in the United States, with about 128,000 kg of macroplastic emissions into the ocean each year (Meijer et al., 2021). Microplastics in the water and sediment of the Delaware River measure an average of 0.19-7.5 particles per cubic meter and 405 particles per kilogram of dry weight, respectively (Baldwin et al., 2021; Cohen et al., 2019). Norfolk Canyon has origins from erosional processes but could still be influenced by river input of the debris in the nearby area of Baltimore Canyon (CSA et al., 2017). Given what we know about the location and internal water movement of the canyons, it is possible that Baltimore and Norfolk canyons have both terrestrial and marine sources of litter. This study aims to determine whether these two canyons are potential conduits of or repositories for debris in the deep sea, and whether this has implications for how the canyon environment is affected by marine debris.

Methods:

Sediment analysis from Norfolk Canyon and the adjacent slope

As part of a larger multidisciplinary study (see CSA et al., 2017), we analyzed sediments collected on Atlantic Deepwater Canyons cruises for microplastics. The 2012 cruise, 15 August to 3 October used the NOAA ship *Nancy Foster* and the 2013 cruise, 30 April to 27 May used the NOAA ship *Ronald H. Brown*. On these cruises, sediment samples were collected along the center axis of Norfolk Canyon (Fig. 1) with a NIOZ design stainless steel box corer (30 cm in diameter, 55 cm in height, 0.07 m^2 in surface area) with a trip valve to seal the top. The box corer was lowered vertically from the ship and once it entered the sediment, the top of the box core was sealed by a lid and the bottom of the box core was sealed by the box core knife. Subsamples were taken from the top 15 cm of sediment in the box cores. Box core samples were collected along two transects (Fig. 1) in the Norfolk Canyon axis ranging from 196 to 1135 m water depth (n=8 cores) and a comparative transect on the adjacent continental slope ranging from 188 to 1118 m water depth (n=6 cores) (Table 1). The adjacent slope is located about 3 km south of the canyon (CSA et al., 2017). Box core sediment samples from within Norfolk Canyon consisted of sandy silty clay with an increasing proportion of clay and a decreasing proportion of sand with depth in the canyon, which was illustrated by an average grain size of 43 μm at the canyon head and 33 μm at the canyon base (Table 2). Box core sediment samples from the adjacent continental slope consisted of sandy silty clay, much like within Norfolk Canyon, but with a larger range of grain sizes than the canyon, which was illustrated by an average grain size of 75 μm in the shallower slope locations and 14 μm in the deeper slope locations (Table 2). Most of the sediment samples were analyzed for benthos (see Robertson et al., 2020). Benthic sediment samples were pre-sieved onboard using a 300 μm stainless steel wet sieve, as per standard benthic sampling protocols, followed by fixation in 10% formalin solution and storage in Nalgene jars. Full details see Robertson et al. (2020). We used this remaining sediment (stored in Nalgene jars) for this study. These sediment samples ranged in surface area from 0.062-0.064 m^2 and ranged in volume from 0.03-2.47 L.

Before opening the samples, we carefully cleaned all laboratory spaces, including laboratory benches, equipment, and fume hoods by washing, drying, wiping with 70% ethanol, and drying again. We only used 100% cotton washcloths in cleaning to eliminate the possibility of contaminating samples with synthetic fibers. We tested cleanliness by sticking tape to all available surfaces and examining for microfibers and microplastics (Courtene-Jones et al., 2017). We performed all separation methods in a fume hood to reduce airborne contamination (Coppock et al., 2017; Van Cauwenberghe et al., 2013). Throughout analysis, we stored the samples in this fume hood to keep them away from potential synthetic contaminants.

To remove possible plastic and debris from the samples, we used a density differentiation method of filtration and flotation similar to the methods outlined in Coppock et al. (2017), substituting sodium iodide (NaI) instead of zinc chloride given what was available to us in the lab. Flotation in sodium iodide is commonly used for finer sediments, such as the silt and clay in Baltimore and Norfolk canyons (Coppock et al., 2017). Sodium iodide has a lower density than zinc chloride but a higher density than sodium chloride, which is the salt solution most commonly used for floatation in literature on microplastics in marine sediment (Harris, 2020). We used a 43 μm mesh filter for all rinses and filters (Loder and Gerdts, 2015). To minimize loss of sediment particles during rinses and treatments, we secured the mesh filter over the top of all sediment jars, drained out the previous solution, and filtered the next solution back through the mesh. First, we rinsed samples with filtered reverse osmosis (RO) water to remove the formalin fixative. Then we drained the RO water from the samples and submerged the samples in saturated NaI for flotation of any plastic particles. We submerged samples in 10mL of NaI, swirled and shook the bottle to allow for a complete rinse with the salt solution, and allowed the sample to settle for floatation of lower density plastic particles (Claessens et al., 2013; Rocha-Santos and Duarte, 2015; Van Cauwenberghe et al., 2013). NaI, which has a lower density (1.8

gcm-3) than sediment (~ 2.65 gcm-3) but a higher density than plastic polymers (~ 0.05-1.4 gcm-3), allows the plastics to float out of the sediment in the saturated salt solution (Rocha-Santos and Duarte, 2015; Hidalgo-ruz et al., 2012). However, as sodium iodide has an intermediate density between other commonly used salt solutions such as sodium chloride and zinc chloride, there is a possibility that our results are underestimates of microplastics in sediment (Harris, 2020). We repeated flotation with NaI three times for maximum extraction of plastic pollutants (Claessens et al., 2013). We identified microplastic and microfiber particles visually given a lack of access to confirmation of exact polymers with Fourier transform infrared spectroscopy (FTIR), the limitations of which we discuss at the end of this paper. We collected floating microplastics by removing the supernatant, placing the supernatant solution under a dissecting microscope, and picking out the possible plastic particles (Law et al., 2010). To dry the collected debris, we placed particles in individual glass dishes and left them in a desiccant chamber for 48 hours. During analysis, we placed a dish of water next to the samples as a blank to test for airborne particle contamination. After retrieving the samples from the desiccant chamber, we counted the number of individual plastic particles found in each sample and used a VWR analytical balance to measure the mass in milligrams. We then measured the maximum linear dimension of each particle and photographed it using a dissecting microscope. Microfiber particles were measured for length.

Univariate and multivariate statistics were performed using PRIMER (PRIMER_E Ltd) statistical software version 7.0 (Clarke and Gorley, 2015). Data were square-root transformed and used to generate Bray-Curtis similarity resemblance matrices. Differences in mean microplastic densities were assessed using univariate ANOSIM (Analysis Of SIMilarity; Clarke 1993) and pairwise comparisons. A two-factor model was used, following a priori defined factors: location (Norfolk Canyon vs Norfolk Slope) and depth levels 1-4 (1: 190 m, 2: 555 m, 3: 800 m, 4: 1110 m).

Video analysis from Norfolk and Baltimore canyons

Researchers recorded high-definition digital video data during the Atlantic Deepwater Canyons cruises using the *Kraken II* ROV (Univ. of Connecticut) in 2012 and the *Jason II* ROV (Woods Hole Oceanographic Inst.) in 2013. Each dive began at the greatest targeted depth and moved upslope (Fig. 4). Thirty-four ROV dives over the two cruises recorded a total of 295 h of bottom video observations at depths ranging from 234-1612 m in both Norfolk and Baltimore canyons (CSA et al., 2017; Ross et al., 2015). ROVs generally moved at slow speeds (0.93 km/h) as close to the bottom as possible with cameras set on wide angle and with parallel scaling lasers with beams 10 cm apart. We identified and quantified any anthropogenic debris seen during analysis of the video for fish communities (see Ross et al., 2015 for details).

Univariate and multivariate statistics were performed using PRIMER (PRIMER_E Ltd) statistical software version 7.0 (Clarke and Gorley, 2015). Data were square-root transformed and used to generate Bray-Curtis similarity resemblance matrices. Differences in mean microplastic densities were assessed using univariate ANOSIM (Analysis Of SIMilarity; Clarke 1993), SIMPER (SIMilarity PERcentages) and pairwise comparisons. A two-factor model was used, following a priori defined factors: location (Norfolk Canyon vs Baltimore Canyon) and depth levels 1-4 (1: 190 m, 2: 555 m, 3: 800 m, 4: 1110 m).

Results:

<u>Sediment data (microplastics) from Norfolk Canyon and the adjacent slope</u>

Debris data are reported here in plastic particles per m^2 of sediment, the same units used by Robertson et al. (2020) for ease of comparing plastic particles to infauna in the canyon sediments.figure Plastic particles per m^2 of sediment were extrapolated from raw data of the number of plastic particles found in each sediment sample using the surface area of the box cores (Table 3). See Table 2 for raw data and Table 3 for extrapolation of further measurements. In this paper, microplastics are defined as particles 0.33-5.0 mm in diameter; all larger particles are defined as macroplastics (Eriksen et al. 2014; Coppock et al. 2017).

Samples from Norfolk Canyon had an average density of 37.30 plastic particles m^{-2} (+/- SD = 23.65 plastic particles m^{-2}) (Fig. 2). These particles ranged from 0.54–13.53 mm in maximum linear dimensions, including one piece of blue monofilament fishing line with a length of 156.0 mm and one blue microfiber (Fig. 7). Eighty-four percent of the plastic particles identified were characterized as microplastics 0.33-5.0 mm in diameter. Sixteen percent of the identified plastic particles were larger than 5.0 mm in diameter. The plastics ranged in mass from 0.04–12.59 mg. The density range was 15.71-78.53 plastic particles m^{-2} (Table 3). The predominant colors of plastic within Norfolk Canyon were white (26%), black (16%), and orange (16%). The largest densities of plastic m^{-2} were found in two samples in the mid-depths of Norfolk Canyon (78.53 particles m^{-2} at 572 m; 62.83 particles m^{-2} at 819 m). The smallest density of plastic m^{-2} was found at 810 m (15.71 particles m^{-2}).

Samples from the adjacent continental slope had an average density of 21.03 plastic particles m^{-2} of sediment (+/- SD = 21.44 plastic particles m^{-2}) (Fig. 2). These particles ranged from 0.43–2.46 mm in maximum linear dimensions (Fig. 8). One hundred percent of the plastic particles identified were characterized as microplastics; no microfibers were found. The microplastics ranged in mass from 0.01–0.35 mg. The density range was 0.00-47.12 plastic particles m^{-2} (Table 3). The predominant colors of plastic particles on the adjacent slope were blue (50%) and white (37%). The largest density of plastic m^{-2} was found in the mid-depths of the canyon (47.12 particles m^{-2} at 550 m). The smallest non-zero plastic particle density was found in one of the highest slope samples (15.71 particles m^{-2} at 188 m).

Using Primer, we created an nMDS plot and applied an ANOSIM to determine the relative contributions of location (canyon or slope) and depth to the microplastic densities found in the sediment samples. nMDS plots are used to show dissimilarity between data points based on distance between points on the plot. On this nMDS plot, which fit to the data well (stress = 0.00), most of the data points were clustered close together, showing similarity. The nMDS plot also showed a separation of the densities of microplastics found in sediment samples from the adjacent slope at 190 m and 800 m (Fig. 3). However, the ANOSIM did not statistically verify this separation and showed that neither location nor depth had a significant effect on the variation between microplastic density on the slope or within the canyon (location $R = 0.008$, $p = 0.41$; depth $R = 0.078$, $p = 0.58$).

Video data (large debris) from Norfolk and Baltimore canyons

Thirteen ROV dives over the two cruises recorded 150.9 h of bottom video observations in Norfolk Canyon at depths of 326-1612 m and 144.1 h of bottom video observations in Baltimore Canyon at depths of 314-923 m (Ross et al., 2015). ROV video from both years revealed that most of the macroplastic debris within Norfolk Canyon was located within the upper to middle reaches of the canyon at a depth range of 300-600 m. Debris items were observed a total of 56 individual times within the 150.9 h of video (Table 4, Fig. 9). The most common items noted were trash, or unidentifiable debris (41%), fishing lines (21%), and trap lines (10%). Other items noted were traps, nets, plastic, a trash bag, a buoy, and a tire (Fig. 5).

ROV video from both years revealed that most of the macroplastic debris within Baltimore Canyon was located within the upper reaches of the canyon at a depth range of 300-400 m. Debris items were observed a total of 76 individual times within the 144.1 h of video (Table 4, Fig. 9). The most common items noted were trap lines (23%) and trash, or unidentifiable debris (16%). Other items noted were fishing lines, traps, plastic, nets, bottles, a trash bag, a can, metal debris, wire, and a crab pot (Fig. 5).

Lighter debris observed in both canyons, such as trash bags, unidentifiable debris, and fishing lines, were often seen caught or tangled on corals such as *Paragorgia arborea* (Fig. 9 A & D). Debris were also observed on the seafloor partially buried under sediment and clustered around aggregations of deep-sea coral and anemones (Fig. 9 B & C).

Using Primer, we ran an ANOSIM to test for differences between location and depths. The tests were non-significant for location (Baltimore versus Norfolk Canyon; $R = 0.016$, $p = 0.337$) but significant for depth groups (190, 555, 800, and 110 m; $R = 0.229$, $p = 0.026$). A further pairwise test showed significantly higher abundances of debris in the upper canyons, specifically in the 190 m versus 555 m depth bounds ($p = 0.027$). A SIMPER analysis showed the types of debris that most contributed to the significant difference between these two depth sites were the amounts of trash, trap lines, fishing lines, and traps that accounted for 73% of the dissimilarity.

Discussion:

Deep-sea submarine canyons are hotspots for accumulation of plastics and other debris (Dominguez-Carrió et al., 2020; Mordecai et al., 2011; Ramirez-Llodra et al., 2011; Woodall et al., 2014). Our study clearly demonstrates the presence of both micro- and macroplastics in two submarine canyons on the Mid-Atlantic Bight, providing further evidence for the eventual settling of plastic to the seafloor. Our study is unique because it focuses on microplastic presence within the sediment samples from the canyon in addition to ROV video data. Two past studies identified microfibers within canyon sediments from the Mediterranean and Northeast Atlantic and found a range of 6.0-40.0 microfibers per 50 mL of sediment and 20.0-70.0 microfibers per 50 mL of sediment respectively (Sanchez-Vidal et al., 2018; Woodall et al., 2014). In comparison our study found a range of 0.07-2.95 microplastics and microfibers per 50 mL of sediment (Table 3). Based on our findings, Norfolk Canyon has a comparatively small amount of microplastics and fibers within canyon sediments than other studied submarine canyons. However, sediments from the Mediterranean could have higher concentrations of microplastics due to their confined nature in a basin, whereas our samples were from submarine canyons on an open shelf environment with less possibility for ocean currents in confined basins to concentrate plastics in a smaller area over time. Another explanation for the smaller quantities of microplastics and microfibers found in sediment from Norfolk Canyon could be distance from possible terrestrial sources of litter such as large population centers in Norfolk, Virginia and the Washington, D.C. area. Sediment studied in the Mediterranean from the aforementioned papers was collected from locations less than 25 km from shore, while Norfolk Canyon rests roughly 56 km offshore of Virginia, U.S.A (CSA et al., 2017; Sanchez-Vidal et al., 2018). Furthermore, the Delaware River, which is close in proximity to both Baltimore and Norfolk Canyons, is on the lower end of the 1000 most polluting rivers in the world in terms of the amount of plastic emitted per year, so the two canyons might not have as large a supply of land-based litter as other submarine canyons (Meijer et al., 2021). We also used sodium iodide instead of the higher density zinc chloride for our method of plastic extraction from the sediment, which could have led to underestimates of plastics in our samples. Nonetheless, microplastics and microfibers were found in every sediment sample in Norfolk Canyon in this study.

One hypothesis on how plastic behaves in deep-sea canyons suggests that litter might accumulate towards the middle and lower parts of canyons, due to down-canyon turbidity currents (Pohl et al., 2020; Van den Beld et al., 2017). These currents often originate in or near the heads of submarine canyons and are known to exist in Norfolk Canyon (Boggs, 2006; CSA et al., 2017). Baltimore Canyon has also been shown to channel turbidity currents and focus internal tides to transport sediments to the deep sea (Gardner, 1989). Sediments entrained within such currents generally settle within canyons in a “fining up” sequence, where larger coarse grain sediments are first to be deposited. Following coarse grain sediments, finer and finer grain sizes are deposited, creating a sedimentation pattern of larger to smaller grain sizes (De Stigter et al., 2007; Mulder et al., 2001). This pattern of settling is clearly demonstrated in the box core sediment samples taken along the center axis of Norfolk Canyon, where above 25 cm the sediment consisted of sandy, silty clay and below 25 cm the sediment consisted of coarse sand (CSA et al., 2017). Subsamples for microplastic analysis were taken from the top 15 cm of the box cores, within the silty clay region of the cores. The sediment accumulation rates within the canyon ranged from 0.13-0.55 g $cm^{-2}y^{-1}$ (CSA et al. 2017). These observations are consistent with sediment profiles prescribed to canyons with down-canyon turbidity currents. In contrast, the sediment samples taken from the adjacent continental slope consisted only of sandy, silty clay and did not have a second deeper layer of coarse sand (CSA et al., 2017). Sediment accumulation rates along the adjacent slope were also lower than within the canyon, ranging from 0.13-0.20 g $cm^{-2}y^{-1}$. This shows that sediment tends to accumulate faster within the canyon than on the adjacent continental slope, which could have implications for how litter accumulates within the canyon.

However, whether this settling sequence also pertains to large debris and microplastic particles has only recently been studied. The behavior and movement of plastic particles in submarine canyons was first modelled in 2013 using typical hydrodynamic behavior of debris to show how pieces and fibers of plastic might be transported through deep-sea environments (Ballent et al., 2013). Subsequent to this model of microplastic transport, Woodall et al. (2014) and Sanchez-Vidal et al. (2018) both found that microfibers tend to occur in higher densities in canyon environments than other environments in the deep sea, such as plains and slopes. These three studies led to the hypothesis that microplastics might be transported through submarine canyons by gravity currents (Kane and Clare, 2019). This conceptualization was then experimentally modelled to show that microplastic accumulation in canyons and subsequent transport to the deep sea by down-canyon turbidity currents is a viable explanation for how microfibers and plastics can find their way to the deep sea (Pohl et al., 2020). Our study reports both microplastics and microfibers in a submarine canyon that occur in higher numbers in the middle reaches of the canyon.

Relevant to the hypothesis of microplastic transport by down-canyon currents, visual observations (ROV video) of macroplastics and other large debris in this study indicated that most larger debris was found within the upper reaches of both Norfolk and Baltimore canyons (Fig. 6). This suggests that if debris are caught within downslope currents or turbidity currents, larger debris may be deposited earlier with heavier, coarse grain sediments, while smaller microplastics may be deposited later with lighter, fine grain sediments (Mulder et al., 2001; Pohl et al., 2020). Recently, studies have confirmed that turbidity currents, as well as other internal canyon currents, are viable explanations for how macroplastics and larger debris are transported through canyons (Zhong and Peng, 2021; Pierdomenico et al., 2019).

The ROV videos and sediment analysis from this study show that larger debris were recorded most often in the higher reaches of the canyon, and microplastics and fibers were recorded most often in the middle reaches of the canyon. However, it is important to note that it is not just the size of particles but their shape and density that determine how plastic will sink or settle in the marine environment (Ballent et al., 2013; Chubarenko et al., 2018). Within the scope of this study, we were unable to identify polymer composition of the particles collected from the sediment samples by floatation and filtration due to a lack of access to FTIR analytical techniques. Consequently, this study is limited in its ability to fully describe the chemical makeup of the particles and how that might have affected their transport to the sediment locations we found them in. This is a crucial detail to be focused on in future work surrounding microplastic and macroplastic analysis in deep-sea sediments to be able to determine how density, rather than only size, influences debris distribution.

However, we can use biological data from within the canyons as well as the size of the debris items to question how varying sizes of debris settle at different locations within the canyons. Larger debris items might accumulate in the higher reaches of the canyons due to the presence of cold-water corals, which are more common in shallower depths, and the possibility of entangling large debris before it is carried down the slope (Mordecai et al., 2011; Ramirez-Llodra et al., 2011; this study). Indeed, in both Norfolk and Baltimore canyons, the most rugged habitats (walls, boulders, and slabs of consolidated sediment,) along with a higher density of sessile invertebrate life, occurred near the heads of the canyons (CSA et al., 2017). Large corals and rocks, which entangle some types of debris, were rare to missing on the open slope near Norfolk Canyon, and the ROV observations that covered open slope habitats rarely noted large plastic debris as commonly seen in the canyon heads. The upper reaches of these canyons may function as accumulation and break-down zones for debris. As plastics, such as those entangled in the corals or rocks (Fig. 9), age and break down into increasingly smaller particles, they likely become more available to downslope transport as evidenced by our sediment core data.

Along with larger invertebrate assemblages found on hard substrate within the canyons, one paper to come out of the Atlantic Deep-Water Canyons Cruises by Robertson et al. shows large densities of infauna found in sediment samples from both Norfolk and Baltimore Canyons (2020). Samples for the Robertson et al. study were taken at the same locations and four depth bounds as our sediment samples in Norfolk Canyon (Fig. 1). Within Norfolk Canyon, the mean density of macrofauna in the sediment was 18,758 individuals m^{-2} (SD +/- ind. m^{-2}). This means that on average, within our sediment samples in Norfolk Canyon, 18,758 infaunal individuals might possibly interact with 37.30 pieces of plastic (the average amount of plastic found in our samples from Norfolk Canyon) in a given square meter of sediment. While it is well known that larger debris negatively affects marine mammals, fish, and invertebrates by entanglement, smothering, or ingesting, the effects of microplastics and microfibers on the smallest of marine organisms is still being understood. Some studies have found sub-lethal effects on marine organisms, such as uptake of persistent organic pollutants or reduced feeding (Bakir et al. 2014; Chua et al. 2014; Matranga and Corsi, 2012). Furthermore, microplastics have already been found in the gut systems of deep-sea invertebrates (Courtene-Jones et al. 2019). Our study uniquely shows the presence of microplastics in sediment with diverse canyon infauna communities, highlighting the importance of understanding potential effects these synthetic particles might have on smaller marine life and the complex invertebrate communities living within these deep canyons.

The ANOSIM analysis for the sediment samples from Norfolk Canyon did not show a significant difference in whether the location or depth of the samples had any effect on the plastic density within the sediment. This might be due to difficulty in acquiring large sample sizes of sediment from deep-sea canyons. The ANOSIM analysis for the ROV video data from Norfolk and Baltimore canyons showed that there was a significant difference between the amounts of debris found in the canyon heads versus the deeper parts of the canyon, though there was no significant difference found between the amounts of debris found in Norfolk versus Baltimore Canyon. This means that while the specific canyon location did not have an effect on the amount of macroplastics recorded, the depth in the canyons does. Our study recorded macroplastics and other debris such as fishing gear and lines in larger quantities near the canyon heads. These amounts of large debris settling at the canyon heads and small debris settling in the middle reaches of Norfolk Canyon provide some evidence for the hypothesis that debris settles in submarine canyons. This debris could also settle within a sequence similar to how large grain sizes of sediment are deposited first before smaller grain sediments out of turbidity currents. This pattern of macro- and microplastic settling could provide insight into how debris is transported from the continental slope to the deep sea through down-canyon currents (Ballent et al., 2013;

Kane and Clare, 2019; Pohl et al., 2020; Sanchez-Vidal et al., 2018; Van den Beld et al., 2017; Woodall et al., 2014).

Conclusions:

Submarine canyons, along with being important conduits of sediment, nutrients and larvae to the abyssal plain, are hotspots of deep-sea biodiversity (Bennett, 1984; CSA et al., 2017; Leo et al., 2010). Areas of high biodiversity, such as cold-water coral reefs, are especially vulnerable to damage by larger anthropogenic litter, which can smother or damage biota, as observed in the ROV video data presented in this paper (Mordecai et al., 2011; Ragnarsson et al., 2017; Van den Beld et al., 2017). Understanding where and to what extent plastic and other debris accumulate within canyons and the deep sea in general can inform efforts to protect and manage these unique environments (Courtene-Jones et al., 2017). Indeed, microplastics have been found consistently in bathyal and abyssal invertebrates and even in amphipods from the deepest ocean trenches (Courtene-Jones et al. 2019; Jamieson et al. 2019). Studying how microplastics move through canyons can also provide insights on how so much of this small debris ends up in more remote deep-sea environments like abyssal plains, seamounts, and hadal trenches (Kane and Clare, 2019; Woodall et al., 2014).

This study is unique because it examines both larger debris and microplastics along a depth gradient within the same two submarine canyons. The microplastics found in the slope and canyon sediments in this study provide evidence for the hypothesis that microplastics might be transported through submarine canyons to the deep sea (Kane and Clare, 2019; Pohl et al., 2020). These microplastics may also interact with the dense and diverse infauna living in the canyon sediments. The macroplastics and other debris recorded in significantly higher quantities in the higher reaches of both Norfolk and Baltimore Canyons also suggest that larger debris might be deposited earlier out of down-canyon currents than smaller microplastics, becoming entangled in, on, and around important benthic invertebrate communities in the canyons. This study provides a step towards finding areas of micro- and macroplastic concentration and transport to understand how debris of all sizes behave in the deep sea.

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Tables:

Table 1. Box core sediment sample locations and water depth from Norfolk Canyon (NF) and the adjacent continental slope (NS).

Sample	**Station**	**Latitude**	**Longitude**	**Water Depth** (m)
Norfolk Canyon				
NF 1	NF-2012-159	37°05’39.84”	74°44’49.92”	196
NF 2	NF-2012-161	37°05’39.84”	74°44’47.27”	197
NF 3	NF-2012-162	37°04’33.60”	74°39’40.31”	573
NF 4	NF-2012-163	37°04’33.60”	74°39’40.31”	572
NF 5	NF-2012-164	37°02’34.44”	74°37’45.11”	819
NF 6	NF-2012-191	37°02’33.72”	74°37’45.11”	810
NF 7	NF-2012-192	37°02’19.31”	74°34’47.63”	1133
NF 8	NF-2012-193	37°02’19.31”	74°34’47.63”	1135
Continental Slope Adjacent to Norfolk Canyon				
NS 1	NF-2012-181	37°01’24.24”	74°38’42.72”	188
NS 2	NF-2012-182	37°01’24.24”	74°38’42.72”	188
NS 3	NF-2012-183	37°00’56.15”	74°34’42.95”	550
NS 4	NF-2012-185	37°00’56.15”	74°34’42.60”	550
NS 5	NF-2013-070	37°00’32.40”	74°33’53.99”	805
NS 6	NF-2013-071	37°00’20.88”	74°32’01.31”	1118

Table 2. Sediment characterization and number of microplastics found in box core samples from Norfolk Canyon (NF) and the adjacent continental slope (NS).

Sample	**Sediment Volume** (L)	**Sediment Grain Size Mean** (μm)	**Sediment Accumulation Rate** (ω (g cm^{-2} y^{-1}))	**Number of Microplastics**
Norfolk Canyon				
NF 1	0.45	43	0.55	3
NF 2	0.41	43	0.55	2
NF 3	0.71	49	0.19	1
NF 4	1.06	49	0.19	5
NF 5	0.39	36	0.22	4
NF 6	0.50	36	0.22	1
NF 7	0.03	33	0.13	2
NF 8	0.03	33	0.13	1
Continental Slope Adjacent to Norfolk Canyon				
NS 1	1.64	75	0.20	0
NS 2	2.47	75	0.20	1
NS 3	3.86	36	0.13	3
NS 4	1.56	36	0.13	3
NS 5	0.21	16	0.14	0
NS 6	0.10	14	0.16	1

Table 3. Extrapolated measurements from number of microplastics in sediment from Norfolk Canyon (NF) and the adjacent continental slope (NS).

Sample	Microplastics per L Sediment	Microplastics per 50 mL Sediment	Mass of Microplastics (g)	Mass of Microplastics per L Sediment (g/L)
Norfolk Canyon				
NF 1	6.60	0.33	1.64	3.61
NF 2	4.85	0.24	0.91	2.21
NF 3	1.41	0.07	2.55	3.60
NF 4	4.73	0.24	1.08	1.02
NF 5	10.23	0.51	0.29	0.74
NF 6	3.61	0.18	12.59	45.47
NF 7	58.94	2.95	5.23	154.14
NF 8	32.15	1.61	0.04	1.29
Continental Slope Adjacent to Norfolk Canyon				
NS 1	0.00	0.00	0.00	0.00
NS 2	0.40	0.02	0.02	0.01
NS 3	2.21	0.11	0.35	0.26
NS 4	1.92	0.10	0.01	0.01
NS 5	0.00	0.00	0.00	0.00
NS 6	9.76	0.49	0.20	1.95

Table 4. Summary of debris in ROV dive video from Norfolk and Baltimore Canyons.

Location	Starting Latitude	Starting Longitude	Ending Latitude	Ending Longitude	Depth range (m)	Debris items recorded
Norfolk Canyon						
ROV-2012-NF-12(Norfolk)	37°03’953	74°39’178	37°04’097	74°38’881	512-638	5
ROV-2012-NF-20(Norfolk)	37°03’058	74°37’939	37°03’038	74°78’198	385-766	13
ROV-2012-NF-25(Norfolk)	37°00’940	74°34’725	37°00’978	74°34’743	541-571	0
ROV-2013-RB-679	37°02’684	74°37’769	37°03’062	74°37’846	617-789	3
ROV-2013-RB-680	37°03’194	74°34’337	37°03’557	74°34’856	422-642	2
ROV-2013-RB-681	37°02’739	74°36’770	37°03’322	74°37’327	412-616	0
ROV-2013-RB-682(seep)	36°51’921	74°29’574	36°52’081	74°29’232	1519-1612	0
ROV-2013-RB-683(seep)	36°52’449	74°28’745	36°52’196	74°29’308	1421-1564	1
ROV-2013-RB-684	37°04’144	74°39’220	37°04’165	74°38’730	320-611	2
ROV-2013-RB-685	37°02’888	74°30’593	37°04’221	74°32’636	539-1390	3
ROV-2013-RB-686	37°03’177	74°36’173	37°03’551	74°36’187	387-622	2
ROV-2013-RB-687	37°03’222	74°34’868	37°03’574	74°34’768	383-715	12
ROV-2013-RB-688	37°01’460	74°35’295	37°01’248	74°35’841	326-561	0
ROV-2013-RB-689(seep)	38°02’847	73°49’044	38°02’883	73°49’315	353-441	5
ROV-2013-RB-690	38°10’231	73°50’262	38°09’609	73°49’953	288-388	7
ROV-2013-RB-691	37°02’004	74°38’025	37°01’821	74°37’941	377-521	1
Baltimore Canyon						
ROV-2012-NF-01	38°08’826	73°50’604	38°08’944	73°50’282	450-634	0
ROV-2012-NF-02	38°08’901	73°50’333	38°08’689	73°50’031	402-530	4
ROV-2012-NF-03	38°06’423	73°48’510	38°07’601	73°48’188	303-827	6
ROV-2012-NF-04	38°05’133	73°47’063	38°06’165	73°47’031	537-1001	1
ROV-2012-NF-05	38°08’276	73°50’155	38°08’245	73°49’997	400-540	0
ROV-2012-NF-06	38°08’377	73°50’144	38°08’820	73°49’969	234-530	4
ROV-2012-NF-07(seep)	38°02’524	73°49’865	38°02’589	73°49’480	412-444	1
ROV-2012-NF-08(seep)	38°03’037	73°49’200	38°03’068	73°49’313	412-454	2
ROV-2012-NF-09	38°09’129	73°50’493	38°09’176	73°50’022	313-574	13
ROV-2012-NF-10	38°10’111	73°51’144	38°09’675	73°51’526	425-574	8
ROV-2012-NF-11	38°05’587	73°48’395	38°05’308	73°49’818	446-938	1
ROV-2012-NF-13	38°09’572	73°51’341	38°09’397	73°51’903	404-478	5
ROV-2012-NF-14(seep)	38°02’602	73°48’899	38°02’951	73°49’326	407-507	5
ROV-2012-NF-15	38°10’263	73°50’627	38°10’686	73°50’449	276-577	11
ROV-2012-NF-16	38°10’627	73°51’666	38°11’349	73°51’378	343-551	6
ROV-2012-NF-17	38°07’020	73°50’479	38°07’114	73°50’867	569-830	0
ROV-2012-NF-18	38°07’022	73°50’738	38°06’931	73°51’001	521-748	0
ROV-2012-NF-19	38°09’317	73°50’436	38°09’099	73°50’118	302-608	8

Figures:

Figure 1. Local bathymetry and box core sampling locations taken in Aug 2012 and May 2013 within Norfolk Canyon (NF) and on the adjacent continental slope (NS). Refer to Fig. 4 for more maps of the sampling area.

Figure 2. Density plastic particles per m^2 of sediment extracted from box core sediment samples in Norfolk Canyon (NF, n=8) and on the adjacent continental slope (NS, n=6). See sampling locations in Fig. 1.

Figure 3. Non-metric multidimensional scaling (nMDS) analysis of density of plastic particles per m^2 of sediment in Norfolk Canyon and the adjacent continental slope. nMDS plots show dissimilarity of sample sets based on distance between the points. Inset figures are examples of microplastics found in Norflok Canyon sediments (A) and the adjacent Norfolk slope (B). Scale bars represent 0.5 mm.

Figure 4. Bathymetric maps of ROV dive transects from Norfolk Canyon (A) and Baltimore Canyon (B). Maps derived from multibeam sonar. Black lines show ROV transect paths. Modified from Ross et al. 2015.

Figure 5. Types of debris recorded in video from 34 ROV dives in both Norfolk and Baltimore canyons in 2012-2013. 295 h of bottom video observations were recorded at depths from 234-1612 m. "Trash" is defined as unidentified debris.

Figure 6. Total number of debris items recorded at each depth range in ROV video footage. The cruises deployed 34 total ROV dives in both Norfolk and Baltimore canyons in 2012-2013. The exact depth was recorded for each debris item observed along the ROV video transect.

Figure 7. Representative sample of microplastics found in Norfolk Canyon (NF) samples (see Fig. 1 for sampling locations). A. NF 1, 196 m. B. NF 2, 197 m. C. NF 5, 819 m. D. NF 5, 819 m. E. NF 5, 819 m. F. NF 7, 1133 m.

Figure 8. Representative sample of microplastics found in adjacent Norfolk Slope (NS) samples (see Fig. 1). A. NS 2, 188 m. B. NS 3, 550 m. C. NS 3, 550 m. D. NS 4, 550 m. E. NS 4, 550 m. F. NS 6, 1118 m.

Figure 9. Representative photos of debris observed in 2012 ROV dives. Dive frames taken by S.W. Ross. A. Plastic (yellow, upper left) entangled on a *Paragorgia arborea* coral from Dive 10. B. Plastic partially buried in the seafloor near anemones from Dive 12. C. Plastic bags (white

and black) and a net near anemones and a crab under the *P. arborea* from Dive 15. D. Plastic entangled on a *P. arborea* coral from Dive 15.

Figure 1.

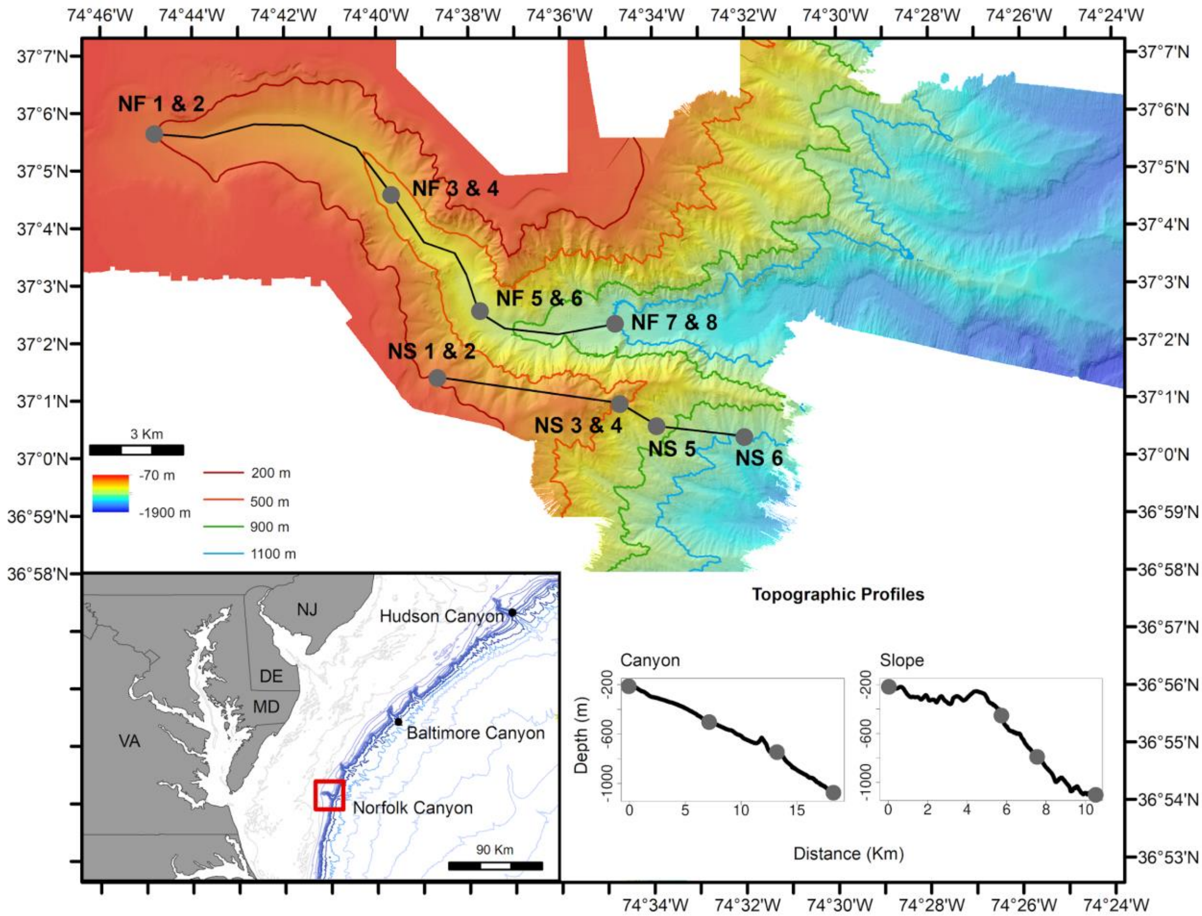
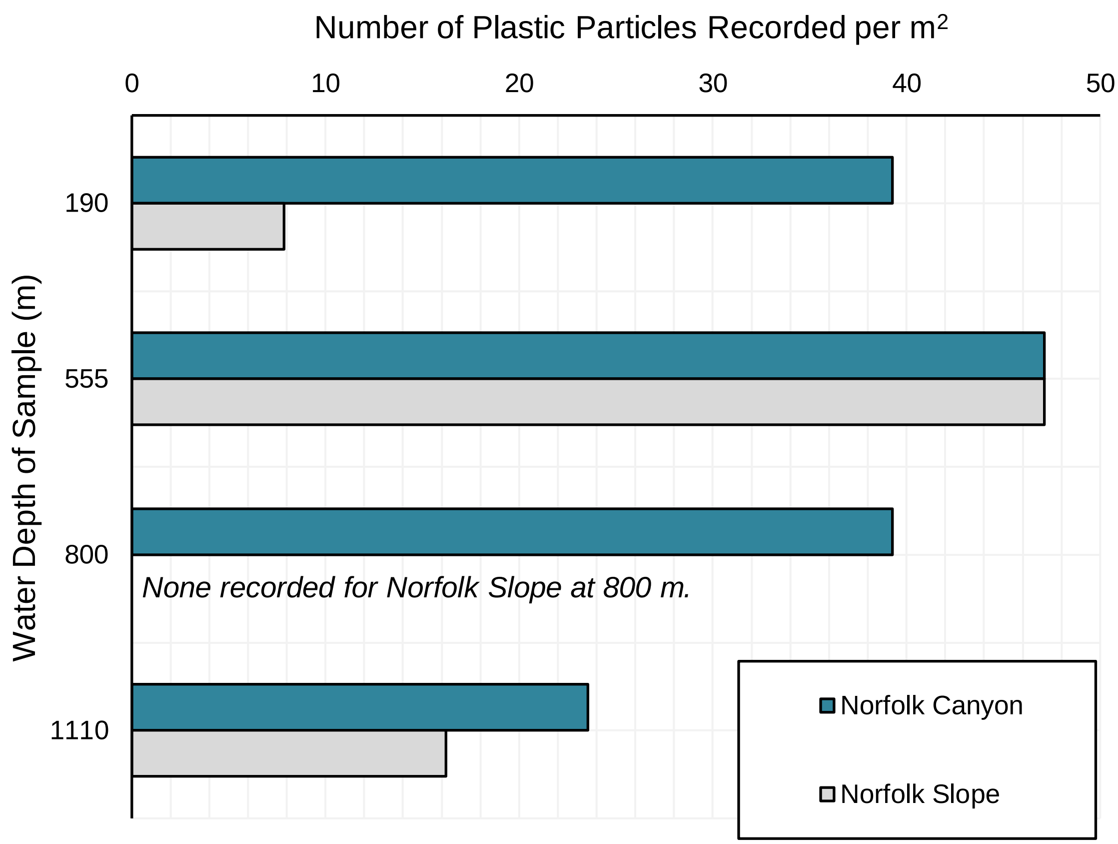


Figure 2.



Number of Plastic Particles Recorded per m2
0
10
20
30
40
50
Water Depth of Sample (m)
190
555
800
1110
None recorded for Norfolk Slope at 800 m.
Norfolk Canyon
Norfolk Slope

Figure 3.

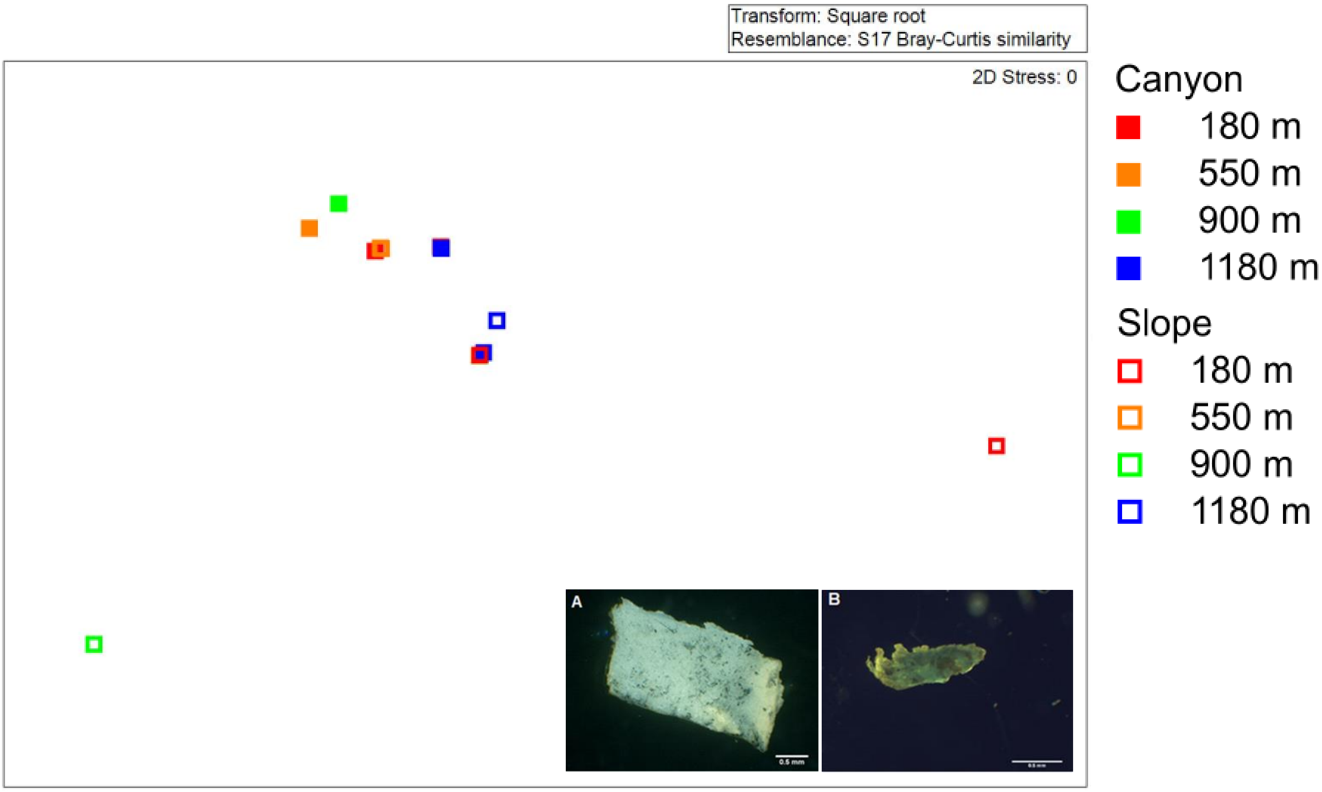

Transform: Square root
Resemblance: S17 Bray-Curtis similarity
2D Stress: 0
Canyon
180 m
550 m
900 m
1180 m
Slope
180 m
550 m
900 m
1180 m
A
B

Figure 4.

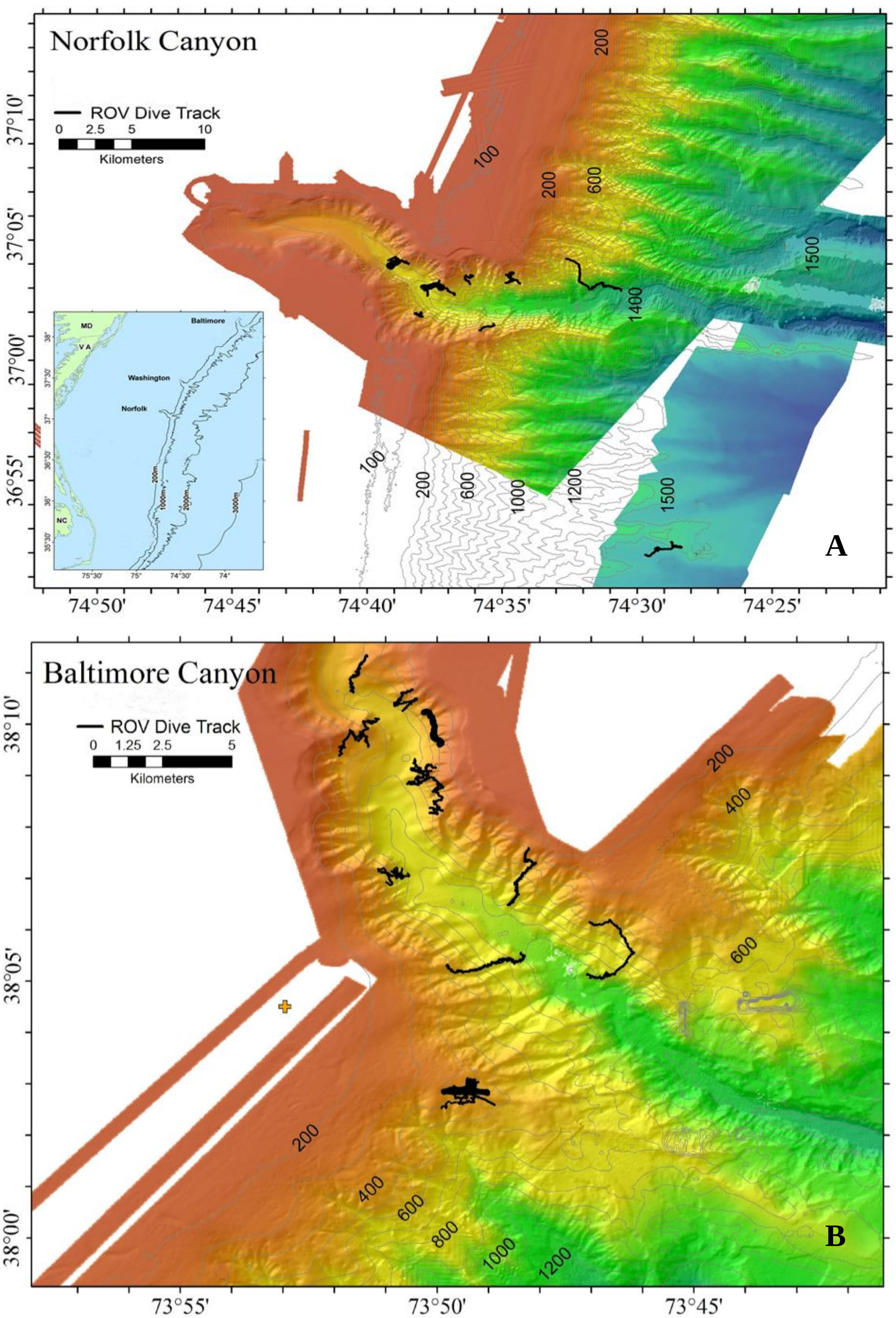

Norfolk Canyon
ROV Dive Track
0 2.5 5 10
Kilometers
37°10'
37°05'
37°00'
36°55'
74°50'
74°45'
74°40'
74°35'
74°30'
74°25'
100
200
600
1000
1200
1400
1500
MD
VA
NC
Baltimore
Washington
Norfolk
A
Baltimore Canyon
ROV Dive Track
0 1.25 2.5 5
Kilometers
38°10'
38°05'
38°00'
73°55'
73°50'
73°45'
200
400
600
800
1000
1200
B

Figure 5.

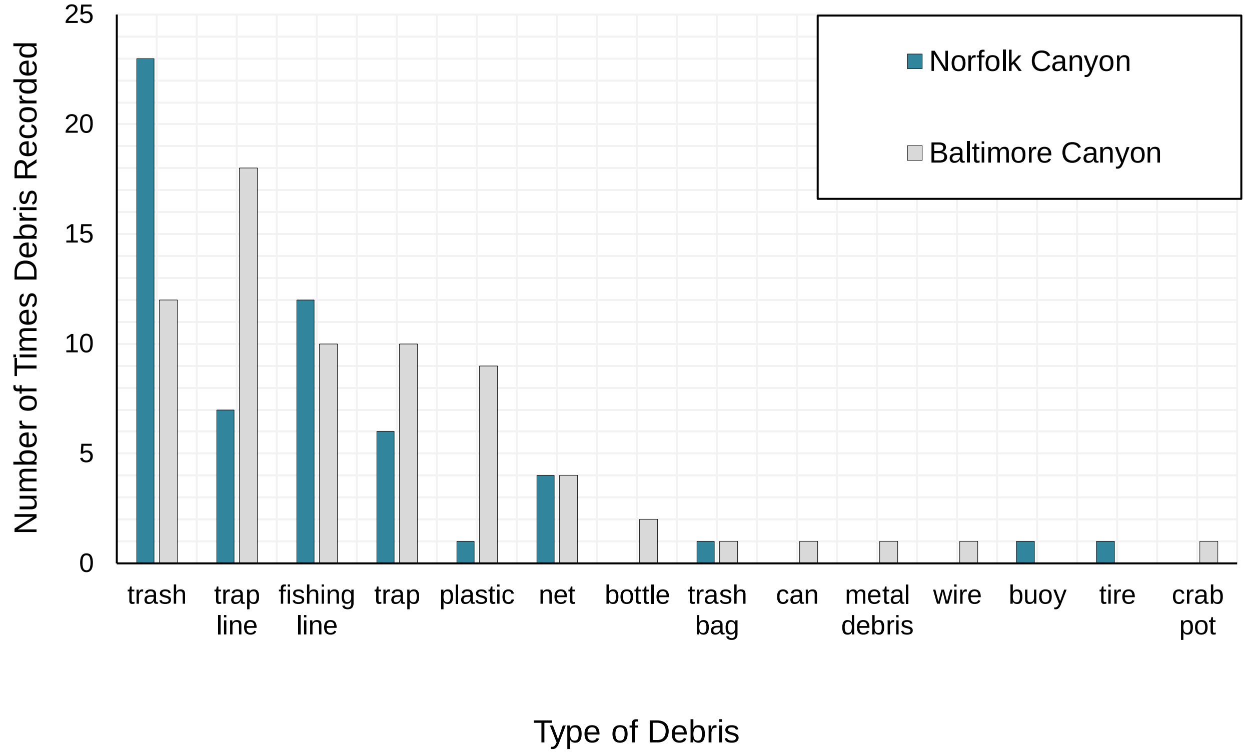

Norfolk Canyon
Baltimore Canyon
Number of Times Debris Recorded
25
20
15
10
5
0
trash
trap line
fishing line
trap
plastic
net
bottle
trash bag
can
metal debris
wire
buoy
tire
crab pot
Type of Debris

Figure 6.

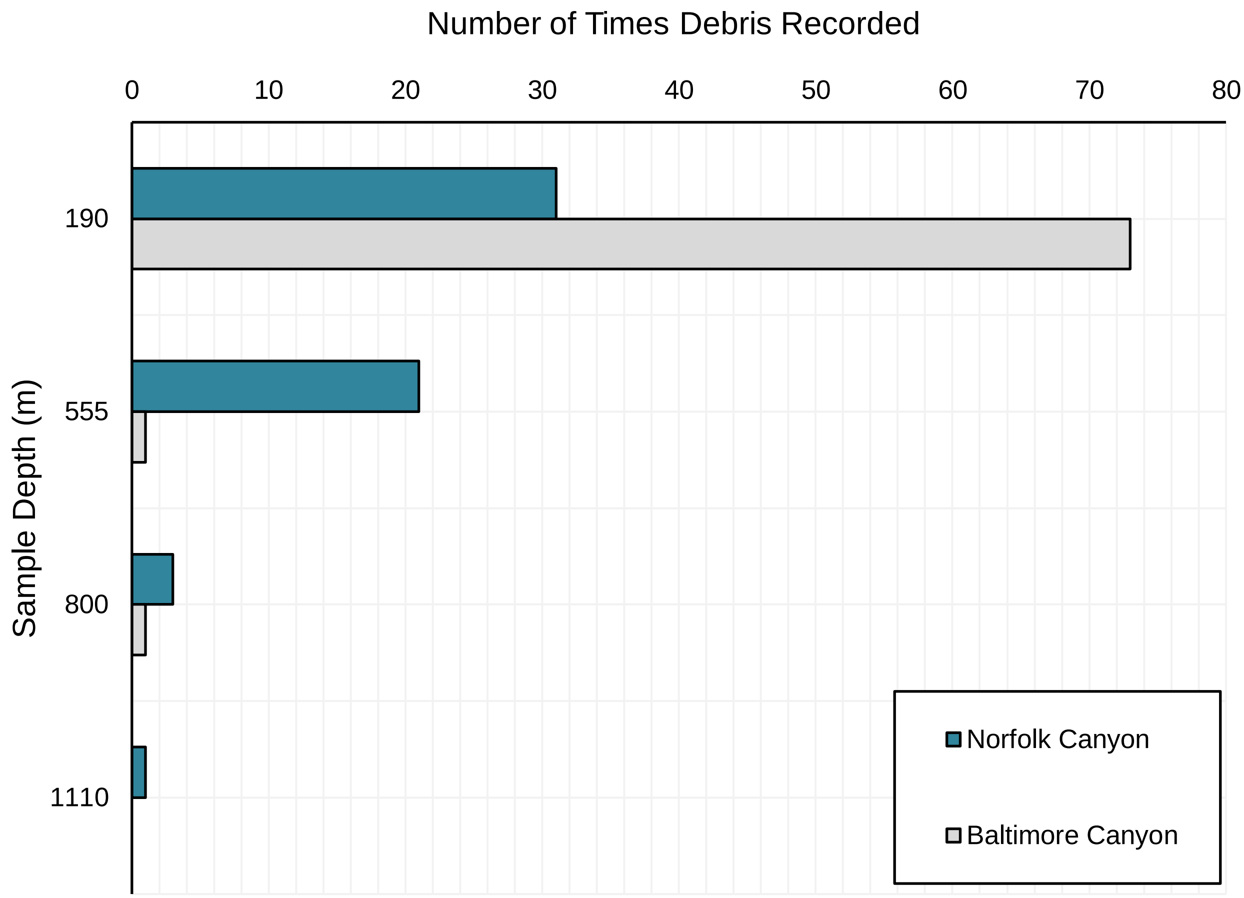

Number of Times Debris Recorded
0
10
20
30
40
50
60
70
80
Sample Depth (m)
190
555
800
1110
Norfolk Canyon
Baltimore Canyon

Figure 7.

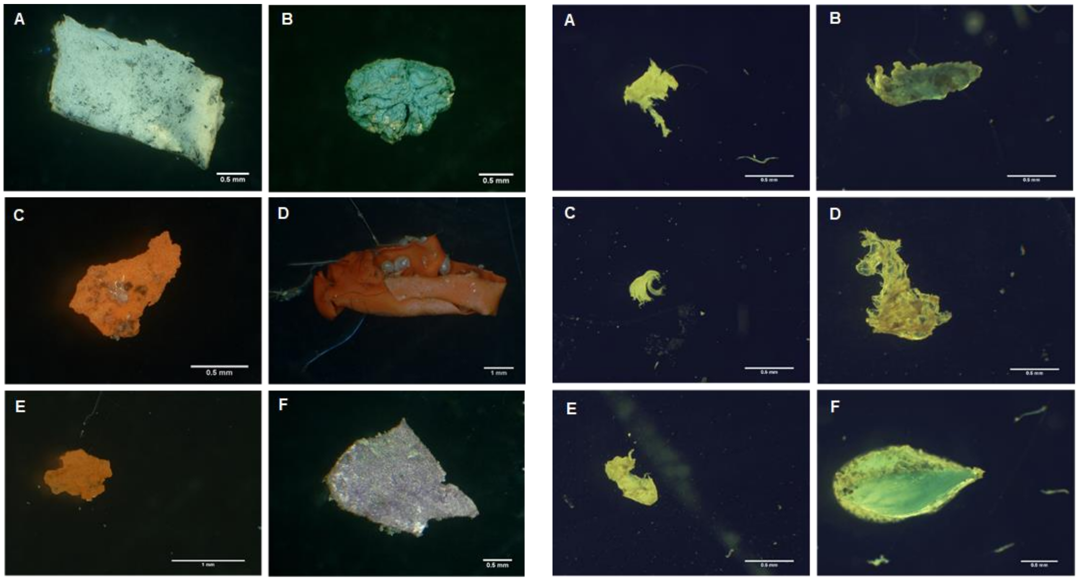
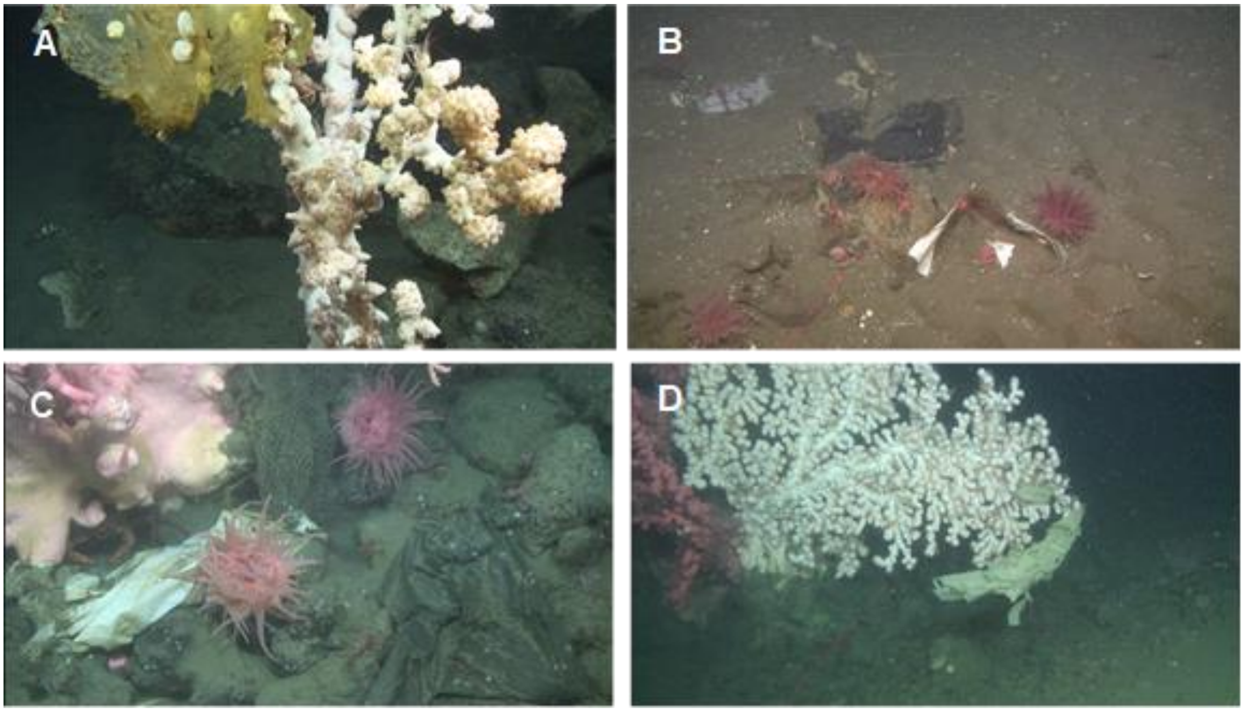


Figure 8.

Figure 9.


A
B
C
D