**Distributions and habitat associations of deep-water corals in Norfolk and Baltimore
canyons, Mid-Atlantic Bight, USA**

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Abstract

A multi-disciplinary study of two major submarine canyons, Baltimore Canyon and Norfolk Canyon, off the US mid-Atlantic coast focused on the ecology and biology of canyon habitats, particularly those supporting deep-sea corals. Historical data on deep-sea corals from these canyons were sparse with less than 750 records for the mid-Atlantic region, with most being soft sediment species. This study substantially increased the number of deep-sea coral records for the target canyons and the region. Large gorgonians were the dominant structure-forming coral taxa on exposed hard substrata, but several species of scleractinians were also documented, including first observations of *Lophelia pertusa* in the mid-Atlantic Bight region. Coral distribution varied

within and between the two canyons, with greater abundance of the octocoral *P. arborea* in Baltimore Canyon, and higher occurrence of stony corals in Norfolk Canyon; these observations reflect the differences in environmental conditions, particularly turbidity between the canyons. Some species have a wide distribution (e.g., *Paragorgia arborea*, *Primnoa resediformis*, *Anthothela grandiflora*), while others are limited to certain habitat types and/or depth zones (e.g. *Paramuricea placomus*, *L. pertusa*, *Solenosmillia variabilis*). The distribution of a species is driven by a combination of factors, which include availability of appropriate physical structure and environmental conditions. Although the diversity of the structure-forming corals (gorgonians, branching scleractinians and large anemones) was low, there were many areas of both canyons that supported high coral abundance and a diverse coral-associated community. The canyons provide suitable habitat for the development of deep sea coral communities that is not readily available elsewhere on the sedimented shelf and slope of the mid-Atlantic Bight

Keywords: Deep-sea corals, canyons, Mid-Atlantic Bight, stony corals, gorgonians, environmental conditions

1. Introduction

Submarine canyons are widespread features with ~5850 identified worldwide (Harris and Whiteway, 2011) connecting continental shelves to deep ocean basins via transport of sediments and nutrients (Bennett et al 1985). With a few exceptions (Hudson and Haedrich 1984; King et al. 2008), canyon communities differ in species composition from those in similar depths outside canyons, and many are biomass hotspots (de Leo et al. 2010). Megafauna are often more abundant in canyons at all depths than on the adjacent slope, whereas on the slope the reverse is often true (Griggs et al. 1969; Rowe 1972; Vetter and Dayton 1998; Carne 2005; de Leo et al. 2010). This phenomenon may be driven by entrainment of terrestrial and marine sediments, and organic material into canyons (Heezen et al. 1955; Keller and Shepard 1978), enhancing food availability in a normally food poor area. Canyons represent areas of high diversity and biomass (including commercial fisheries) in the deep sea (Stefanescu et al. 1994; Gartner et al. 2008; de Leo et al. 2010), likely due to high levels of environmental heterogeneity, e.g. in physical structure, hydrography, and geological activity, which creates spatial and temporal heterogeneity in sedimentation rates, substrata, food and environmental factors (Vetter and Dayton 1999; Allen et al. 2001; Kuhnze et al. 2002; Buhl-Mortensen et al. 2010). This complex interplay of factors contributes to the observed patchiness in faunal assemblages (McClain and Barry 2010). Exposed hard substrata are common in canyons and generally found where currents are strong on outcrops or relict shorelines along canyon walls, and sometimes along the canyon thalweg, where boulders have been carried by turbidity flows (Stanley and Fenner 1973; Hecker et al. 1980; Malahoff et al. 1982). Hard substrata often support dense communities of sessile suspension and filter feeders, such as cnidarians and sponges, which provide habitat for diverse and abundant faunal assemblages. Canyons may also provide refuge for demersal fish species as

bottom tending fishing gear cannot be easily operated in the rugged topography of submarine canyons (Huvenne et al 2011). Their large size, complex topography and fast currents make canyons some of the most challenging of deep-sea environments to explore. Underwater vehicles are the most effective tools for surveying and sampling canyon habitats and communities and their use in recent years has greatly increased our understanding of canyon ecology and processes.

The U.S. Atlantic margin north of Cape Hatteras contains between 30 and 40 submarine canyons; at least 13 of these are considered major canyons within the Mid-Atlantic Bight (MAB) region (Andrews et al., 2013), which extends from Cape Hatteras, North Carolina to Cape Cod on the east coast of the U.S.A. The canyons vary in size, shape, and topographic complexity; some are the product of ancient riverine systems (e.g., Wilmington, Hudson), but most formed via other erosional processes, such as slides, debris flows, and turbidity currents (Uchupi 1968; Malahoff et al. 1980; Tucholke 1987, Obelcz et al 2014).

Early work in the MAB canyons included some submersible dives and towed camera surveys to conduct anthropogenic impact studies (Cooper et al 1992, Able 2002), fisheries surveys (Grimes et al 1987) and studies of benthic epifauna (Hecker et al 1980, 1983). These studies revealed a wide range of habitat types including soft sediments, cobbles, rocky outcroppings and extensive excavations by fish and invertebrates (Grimes et al. 1987; Tucholke 1987). Visual surveys revealed deep sea coral communities, which were dominated by octocorals, solitary scleractinians, and anemones (Cairns 1981; Watling and Auster 2005; Packer et al. 2007), rather than the reef-forming stony corals (*Lophelia pertusa*, *Enallopsammia profunda*) that are the foundation of deep sea coral communities in the southeastern U.S. and Gulf of Mexico (Brooke and Schroeder 2007; Ross and Nizinski 2007). A comprehensive compilation of deep-sea

octocoral (Alcyonaria) observations in the northeastern US (Cape Hatteras to the Canadian border) contains 761 records (Watling et al. 2003). These records fall into two distinct time periods: 1874-1920 and 1950-2001. The earlier records were primarily incidental catches from US vessels that were taking dredge hauls as part of mapping and geological studies (summarized by Deichmann, 1936). The later time period included visual surveys for fisheries, energy industry surveys and ocean dumping projects (Hecker et al., 1980, 1983, Malahoff et al., 1982, Grimes et al., 1987, Cooper et al., 1992, Able 2002). This database included 10 families and 25 species (Watling and Auster, 2005), and with the exception of the *Acanella* sp., these were hard-substrate taxa. The NOAA Deep Sea Coral Research and Technology Program (DSCRTP) deep sea coral data portal lists 166 records of gorgonians, 98 soft corals and 455 sea pens for the MAB alone. For the scleractinia, the data portal has 334 records for the MAB, of which ~200 are soft sediment taxa such as *Flabellum* and *Dasmomilia*. In soft sediments of the western Atlantic slope, additional sessile cnidarians include pennatulids and burrowing cerianthid anemones; these species are also found in soft sediments within the canyons (Shepard et al. 1986; Packer et al. 2007).

The use of submersibles, ROVs, AUVs and towed cameras has facilitated exploration of topographically complex features such as canyons, and recently, several U. S. federal agencies (NOAA, BOEM, USGS) have supported geological and biological surveys of the MAB and New England canyons (Quattrini et al 2015, Obelcz et al 2014, Skarke et al 2014, Pierdomenico et al 2012). These studies resulted in range extensions for octocoral and fish species (Quattrini et al. 2015) and new observations of *L. pertusa* for the MAB region (Brooke and Ross 2014). Although the importance of deep-sea corals to other macrofauna has not been fully established (Auster 2007; Purser et al. 2013; Ross et al. 2015), deep-sea corals nevertheless contribute

substantial structure and complexity to MAB canyon benthic habitats (Hecker et al 1980; Brooke and Ross 2014; Ross et al. 2015).

Data reported in this manuscript was generated by a large multi-disciplinary study of two MAB canyons: Baltimore Canyon and Norfolk Canyon. One of the objectives of this study was to explore and characterize the little known hard-substrata habitats and their associated communities within these canyons, and relate the distribution of structure forming corals with geological and environmental variables to identify potential drivers of species distributions and community structure both within and between canyons.

2. Materials and methods

2.1 Study area

This study concentrated on Baltimore and Norfolk canyons and the immediate surrounding slope areas (Fig. 1). These large, shelf-sourced canyons have rugged terrain mostly on the north sides and near the canyon heads, including a series of terraces that stepped down many of the canyon walls (Obelcz et al. 2014). Hard substrata mostly consisted of ridges and walls of consolidated mud, rocks, and talus fields (Tucholke 1987; authors pers. obs.). The MAB slope is impinged by several different water masses at different depths that provide diagnostic signatures in temperature and salinity; the water masses pertinent to this study are the North Atlantic Central Water (< 500 m depth, 7-20°C, 35-36) and the Western Atlantic Subarctic Intermediate Water (500-1500 m depth, 3-9°C, 33-35) (Csanady and Hamilton 1988, Csanady et al 1988). The cyclonic Slope Sea Gyre dominates larger scale surface water movement in the MAB (Brooks 1996), with periodic meanders of the Gulf Stream that cause upwelling and shoreward movement

of nutrient rich waters (Fitzgerald and Chamberlin 1981). However, tidal currents and internal waves are the major forcing functions for upwelling and down-welling flows along canyon axes (Keller and Shepard 1978, Allen and Durrieux de Madron 2009). Turbidity within canyons is higher than on the adjacent slope and an upper slope nepheloid layer occurs in both canyons, but particularly Baltimore Canyon (Gardner 1989).

Prior to the current study, images of deep sea corals from within Baltimore and Norfolk canyons came primarily from studies by Hecker and colleagues (Hecker et al 1980, 1983). They documented abundant gorgonians (*P. arborea*, *P. resedaeformis*, *A. armata*), soft corals and dense assemblages of anemones, particularly on the northern and western walls of Baltimore Canyon and the north and south walls of Norfolk Canyon at depths of ~160-600m. Analysis of these and other historical visual materials, in combination with multibeam maps of the canyons (generated during the current study), were used to target ROV dives.

2.2 Field methods

The 2012 research cruise (17 Aug - 14 Sep 2012) used the NOAA Ship Nancy Foster and the ROV *Kraken II* (Univ. of Connecticut). This was a Max Rover science-configured ROV with an operating depth of 1000 m and was equipped with a Kongsberg OE14-502 high definition (HD) video camera mounted on a pan and tilt and with parallel lasers (10 cm apart) for scaling, Kongsberg OE13-408 digital still camera (10 MP), five-function manipulator arm and a hydraulic collection platform with a suite of collecting containers. The vehicle also had a rotating carousel of 8 buckets that is connected to a suction sampler for collecting small mobile or delicate samples. The ROVs position was continuously recorded using an ORE Trackpoint II

Ultrashort Baseline tracking system combined with a Winfrog integrated navigation system, which allowed near real-time view of the ROV position.

The 2013 research cruise (2-18 May 2013) used the NOAA Ship *Ronald H. Brown* and the ROV *Jason II* (Woods Hole Oceanographic Inst.), which can operate to 6500 m. The science camera on the ROV was an Insite Mini-Zeus HD video camera with parallel lasers (10 cm apart) for scaling. There were two digital still cameras: a Nikon CoolPix (3 MP) and an Insite Super Scorpio (3.34 MP). Two seven-function hydraulic manipulator arms were used to collect samples. A retractable sled on the front of the ROV and was equipped with sampling devices, as well as a carousel of 6 buckets with a suction sampler. The ROV navigation system was a Sonardyne Ranger Ultra Short Baseline (USBL), allowing a near real-time view of the ROV position.

Prior to each ROV dive, a color-shaded bathymetric GeoTiff map of the dive site was provided (these were products of a multibeam mapping cruise using the NOAA Ship *Nancy Foster* in 2011) and used to guide the dives. The ROVs conducted standardized video transects of variable distances across multiple habitat types while moving at slow speeds (< 0.5 kts). During transects, the color video cameras with scaling lasers were set on wide angle and positioned to record in front of the ROV. Digital still images were taken frequently to augment the digital video and to assist in species identifications. Collections of specimens were accomplished using the manipulator arm, which transferred samples to a variety of containers attached to the ROV sampling platform. Every sample was documented with video, and collection data was recorded. Data for physical variables were collected around the habitats of interest using a Seabird SBE 19+ data logger attached to the ROVs, which recorded conductivity ($\mu\text{S}/\text{cm}$), temperature ($^{\circ}\text{C}$), depth (m), density (σ_{θ} , kg m^{-3}), dissolved oxygen (DO, ml/L), pH

and turbidity (formazin turbidity units) at a frequency of once per second during each dive. Two Niskin bottles were mounted on the ROVs to make near-benthic water collections that were subsequently analyzed for carbonate chemistry. ROV position (ultra-short baseline tracking) data were time-synchronized with all imagery, collections and environmental data.

A small (5 m) otter trawl was used to make off-canyon collections of benthic fauna. The net was deployed at depths between 150-1700 m for 30 minute intervals over soft sediment habitats on the slopes adjacent to the target canyons. Both vessels had a CTD carousel with an array of 12 Niskin bottles (5 L on the *Nancy Foster*; 10 L on the *Ronald H. Brown*). Water samples were collected (during the upcast) from near surface, mid-water and near bottom over a depth range of 97-1032 m in Baltimore Canyon and 100-1387 m in Norfolk canyons. These samples were used for analysis of carbonate chemistry.

2.3 Habitat and community analysis

The ROV navigation files (including latitude, longitude and depth) and the dive videos were synchronized via their time codes so that position and depth data could be assigned to observations on the video. Video from the ROV dives was only analysed when the vehicle was in transect configuration (Section 2.2) with lasers on and with adequate visibility to enable habitat and faunal descriptions. All poor quality video and sections where the ROV was stationary (usually for sampling) were removed. The remainder of the video was categorized into one of six geological habitat types, which encompassed the dominant combinations of soft and hard substrata found in the canyons (Table 1; Fig. 2). In addition to these structural categories, the video data were further classified according to percentage cover (<25%, 25-75%, >75%) of structure forming cnidarians (SFC) and type of SFC (large corals, large anemones/cup

corals, and mixed) (Table 1). The habitat analysis generated georeferenced habitat types and percent cover of SFC, which were used to create maps of dive tracks with habitat and SFC superimposed on bathymetry collected with multibeam sonar in previous cruises.

To generate high-resolution information with uniform-sized replicates, video of each habitat category was split into one-minute intervals; segments of habitat type that were less than one minute were discarded. For each time interval, all corals and large anemones were counted. Coral distributions were analyzed using multivariate statistics (Primer-E V6 software; Clarke and Gorley 2006) to determine whether there were significant differences between factors (canyon, ROV dive, and habitat type). Prior to analysis, a fourth root transform was applied to the frequency count data to reduce the dominance of very abundant species. Bray-Curtis similarity matrices were created and multi-dimensional scaling (MDS) plots were generated for corals by each factor. Records of *Keratoisis cf grayi* and the Antipathidae were removed from the analysis as they were either absent or rare (< 10 records) in one or both canyons, and/or their taxonomy was uncertain. A two-way analysis of similarity (ANOSIM) was used to analyze differences in coral abundance by dive, nested within canyon. A one-way ANOSIM was used to determine the effect of habitat type.

2.4 Physical environment

Data from the Seabird (SBE 19+) instrument attached to the ROVs were incorporated into the habitat and community analysis data sheets by cross referencing the time stamps on the data from the instrument, with the ROV navigation files. This process created geo-referenced coral location data with environmental conditions. These data were used in statistical analyses to identify potential environmental drivers for the observed coral distributions. A spearman Rank

correlation analysis was performed on the environmental data from all coral records, to identify redundant variables (i.e. those with $\rho > 0.95$ or < -0.95). Environmental data were square root transformed and normalized. The BEST routine (Primer-E V6) was used to generate correlations between environmental data and coral abundance. Principle component analysis (PCA) was used to determine which environmental variables had the greatest contribution to coral abundances. To determine whether the relationship between environmental variables and coral abundance is statistically significant, the RELATE routine (Primer-E V6) was applied to the matched resemblance matrices for coral abundance (Bray-Curtis) and environmental data (Euclidean) using a Spearman Rank correlation.

Water samples were taken from Niskin bottles attached to the ROV and from near-bottom collections made during the CTD casts. These were analyzed by NOAA Pacific Marine Environmental Laboratory, who measured dissolved organic carbon (DIC, $\mu\text{mol/kg}$) and total alkalinity (TA, $\mu\text{mol/kg}$) using standard analytical techniques (Dickson et al 2007). Levels of other parameters of interest were calculated using DIC and TA measurements; these include CO_2 ($\mu\text{mol/kg}$), HCO_3^- ($\mu\text{mol/kg}$), CO_3^{2-} ($\mu\text{mol/kg}$) and saturation states of Aragonite ($\Omega_{\text{Arag.}}$) and Calcite (Ω_{Calcite}). Since carbonate chemistry may influence the distribution of both octocorals and stony corals, these data are presented and discussed.

3. Results

3.1 Habitat and community analysis

During the 2012 cruise, the ROV *Kraken II* made 17 dives that targeted coral/hard-bottom habitats over a depth range of 234-1001 m; 15 dives were made in Baltimore Canyon and two in

Norfolk Canyon. In 2013, the ROV *Jason II* made 10 dives on coral/hard-bottom habitats, one in Baltimore Canyon (288-388 m), and the remaining nine in Norfolk Canyon (320-1390 m). The ROV dives from both years combined, generated 2,542 minutes (~42.4 hours) of video for habitat/community analysis of Baltimore Canyon, and 2,198 minutes (~36.6 hours) for Norfolk Canyon. The total number of observations of each coral taxon by canyon, together with the range of depths, habitat types and environmental conditions are summarized in Table 2. To visualize the habitat and coral distribution data, two maps were constructed for each ROV dive; habitat maps comprised habitat data (extracted during video analysis) that was superimposed along the ROV dive track. Coral distribution maps were generated by overlaying coral locations along each ROV dive track. Both tracklines were overlaid on local bathymetry to provide topographic context for the data. These maps are presented as supplementary material (SM Fig. 1).

Species richness of corals was low in both canyons with locally high abundance for some species (Table 2); however, richness of other sessile hard substrate fauna was higher, particularly for anemones and sponges. In addition to the large anemones that were counted as SFC, there were numerous smaller anemones, which often occurred in large patches of a single ‘species’ (as defined by size and color variations but most of these were not sampled and identified) on exposed hard substrata. Sponges were more diverse, with > 30 different morphotypes of hexactinellid and demosponges recorded during video analysis.

Octocoral species that were observed in both canyons included the gorgonians (Order Gorgonacea) *Paragorgia arborea* (Fig. 3A) *Primnoa resedaeformis* (Fig. 3B) *Anthothela grandiflora* (Fig. 3C), *Paramuricea placomus* (Fig. 3D), as well as the soft corals (Order Alcyonacea) *Duva florida* (Fig. 3E) and *Anthomastus* sp. (Fig. 3F). A cryptic species and possibly a cryptic genus have been identified for *A. grandiflora* (Clostio and France, in review);

however, since it is not possible to distinguish between these taxa visually, *A. grandiflora* will be used to represent this taxonomic complex. The small, yellow gorgonian *Acanthogorgia aspera* (Fig. 3G) was common in Norfolk Canyon, but was not observed in Baltimore Canyon. Bamboo corals (Gorgonacea, Isididae) (Fig. 3H) were observed infrequently in the canyon habitats, but large numbers of the soft-sediment bamboo coral *Acanella arbuscula* (Fig. 3I) plus some sea pens (Order Pennatulacea) were collected in five deep trawls (1576-1694 m) conducted in Norfolk Canyon.

Hexacoral taxa that were observed in both canyons included stony corals such as *Lophelia pertusa* (Fig. 4A) and the cup corals, *Javania* sp. and *Desmophyllum dianthus* (Order Scleractinia) (Fig. 4B, C), the yellow zoonthid (Order Zoantharia) (Fig. 4D), and large anemones (Order Actinaria) (Fig. 4E-G). The scleractinians *Solenosmilia variabilis* and *Flabellum alabastrum* (Fig. 4H, I), and black corals (Order Antipatharia), such as *Telopathes magna* (Fig. 4J), were only found in the deeper areas of Norfolk Canyon (> 956 m) and were not observed in Baltimore Canyon, possibly because of the limited number of deep dives (three > 800 m) in Baltimore Canyon. The distribution of coral species collected with the ROV within Baltimore Canyon is presented in Figure 5A, B and within Norfolk Canyon in Figure 6A, B. Soft-sediment cup corals were also collected using otter trawls from near the head of Baltimore Canyon at ~270 m depth (*Dasmosmilia lymani*) and from Norfolk Canyon at 1500 m depth (*Flabellum alabastrum*).

Both octocorals and hexacorals were observed predominantly on walls and steep slopes and on large boulders of rock or consolidated sediment. Colonies of the gorgonian *Paramuricea placomus*; however, were observed in one location in each canyon, both times on flat pavement with sediment cover rather than on the walls, overhanging ledges or boulders which were more

typical for the gorgonians (Table 2). On occasion, large amounts of apparently suitable habitat such as steep rocky walls were observed, but with very few corals (ROV-2012-NF-17; SM Fig. 1). Some of the habitat maps indicate high SFC cover, but had no octocorals or stony corals; these areas were dominated by large anemones (e.g., *Bolocera tunediae*, *Actinoscyphia* sp.) or Cerianthidae (tube-dwelling anemones). Areas dominated by large anemones occurred frequently in both Baltimore Canyon (SM Fig. 1, ROV-2012-NF-02, 13, 15, 16) and Norfolk Canyon (SM Fig. 1, ROV-2013-RB-686, 688, 691). The common gorgonians *P. arborea*, *P. resedaeformis*, *A. grandiflora*, *A. aspera*, (Table 2), and the Parazoanthidae (which grows over gorgonian colonies) were all found in a wide range of hard substrate habitats (Table 2), whereas other species were found under more restricted conditions; for example *L. pertusa* was observed only on steep walls within a depth range of 374-424 m (Table 2) and *S. variabilis* was only observed deeper than 1250 m.

The number of observations per hour of ROV transect time were calculated for each octocoral and hexacoral taxa documented during video analysis of each canyon (Fig. 7 and 8). The most common species overall was *Desmophyllum dianthus*, with > 34,000 records; however, most (> 30,000) of these were from one long (~2.5 km) wall in Norfolk Canyon between 1190 m and 1390 m depth (SM Fig 1. ROV-2013-RB-685). A steep wall on the western flank of Baltimore Canyon also had several clusters of this cup coral (SM Fig. 1, ROV-2012-NF-17, 18), but *D. dianthus* were generally observed in groups of 1-3 individuals. Of the gorgonians, *P. arborea* was the most common in both canyons, although there were more observations in Baltimore than Norfolk Canyon. These colonies were also by far the largest of the corals observed, often reaching over 2 m in height and width. The soft coral, *Duva florida* was locally

very abundant in both canyons, but was not observed frequently, although the habitats where they were found were similar to those for the other gorgonians (Table 2).

Octocorals included in the statistical analyses were *Paragorgia arborea*, *Primnoa resedaeformis*, *Paramuricea placomus*, *Anthothela grandiflora*, *Acanthogorgia aspera* and *D. florida*, and hexacorals included *Lophelia pertusa*, *Desmophyllum dianthus*, *Solenosmilia variabilis*, and Parazonathidae. A two-way analysis of similarity (ANOSIM) for ROV dives nested within canyons showed significant differences in distribution by canyon ($R=0.123$, $p < 0.05$) and by dive ($R=0.500$, $p < 0.001$). Multi-dimensional scaling (MDS) plots are shown for coral abundance by canyon (Fig. 9A) and by ROV dive number (Fig. 9B); in the latter figure, all the coral records from the deepest dive (ROV-2013-RB-685, 1257-1398 m) are clustered together with little overlap with other dives. The corals observed on this long steep wall included the only observations of *S. variabilis* and the black coral *T. magna* as well as extremely high numbers of *D. dianthus*. The ANOSIM was re-run excluding this atypical dive but the statistical outcome did not change, therefore these observations are not driving the statistical differences between canyons and among dives.

A one-way ANOSIM showed significant differences in coral abundance by habitat type ($R=0.125$, $p < 0.001$), with the greatest differences between the habitat extremes such as soft sediment and walls ($R = 0.511$, $p < 0.001$) and no significant differences ($R = -0.031$, $p = 0.88$) between habitats that were relatively similar such as SR (< 50% hard substrata) and R (> 50% hard substrata). An MDS plot is shown for coral abundance by habitat type (Fig. 9C).

A Spearman Rank Correlation test showed significant correlations between temperature and salinity ($\rho = 0.95$) and between temperature and density ($\rho = 0.99$), so salinity and density were removed from further analysis (correlations among all variables are shown in Table 3). The BEST

routine (Primer-E V6) applied to the environmental data and coral abundance similarity matrix (Bray-Curtis) showed that depth had the greatest correlation with coral distribution ($\rho = 0.395$), followed by depth and temperature combined ($\rho = 0.378$). Turbidity ($\rho = 0.356$), pH ($\rho = 0.332$), or oxygen ($\rho = 0.317$) in addition to temperature and depth showed decreasing correlations with coral abundance.

Principle component analysis (PCA) on coral environmental data (Fig. 10) resulted in the highest coefficients for temperature and depth in PC1 (0.636, 0.515), followed by oxygen (0.492), pH (0.270) and turbidity (0.122). In PC2, the ranks of these variables were exactly reversed. Together, PC1 and PC2 accounted for 79.7% of the variation. The RELATE analysis showed a statistically significant relationship between environmental variables and coral abundance ($\rho = 0.291$, $p = 0.001$).

3.2 Physical environment

The average ($\pm$ SD) and range of environmental data collected during all the ROV dives (SM Table 1) reflected only near-bottom conditions during the dives, and depth data are provided for reference. Each variable showed depth related trends; temperature and salinity decrease and density increases with depth similarly for both canyons (Fig. 11A, B, C). The relationship between depth and each of these variables was non-linear; beyond approximately 600 m depth, the curves flatten and there was less change with increasing depth. Oxygen and pH generally increased with depth (Fig. 11D, E), but oxygen levels were generally lower in Norfolk Canyon than Baltimore at comparable depths. Turbidity was variable for both canyons with highest turbidity at mid-depths (600-800 m), and consistently lower at depths >1000 m (Fig. 11F). Carbonate chemistry of water samples also reflected primarily near-bottom conditions; however

midwater and near surface samples were collected with the CTD in both canyons (SM Table 2). Aragonite saturation state (Ω_{Arag}) values ranged from 2.27 near the surface (~100 m) to 1.2 at the deepest point measures (1387). Between 100 and 250 m depth, the Ω_{Arag} declined rapidly from ~2.3 to 1.6, then declined more slowly with depth to a minimum of ~1.2 (Fig. 12).

4. Discussion

The data from our study substantially increased the number of deep coral observations for the MAB region; these included new observations of *Lophelia pertusa* for Norfolk and Baltimore canyons (Brooke and Ross 2014) and new records of *Solenosmilia variabilis* and the black coral *Telopathes magna* for Norfolk Canyon. In addition to the deep coral communities, two methane seeps were documented during this study in Baltimore Canyon (410-430 m) and Norfolk Canyon (1500-1600 m). Recent surveys have revealed an additional ~ 570 gas seepage sites along the western Atlantic margin, although few have been ground-truthed to date (Skarke et al. 2014, Quattrini et al. 2015). Several colonies of *P. arborea* were observed on authigenic carbonate (a byproduct of bacterial metabolism of methane) at the Baltimore Canyon seep. These carbonates, while somewhat limited in area, can provide habitat for sessile benthic fauna in otherwise soft-sediment environments.

Surveys of steep canyon walls in the NE Atlantic revealed previously unknown aggregations of *L. pertusa* (Huvenne et al. 2011), and exploration of canyons in the northeastern US documented new deep coral communities and methane seeps (Quattrini et al. 2015). Such data illustrate that a modest number of visual surveys can yield large amounts of new information from poorly studied habitats. Although several range extensions have been reported no new coral species (with the exception of the cryptic *Anthothela*) have been discovered, indicating that the

canyons, at least for these taxa are providing habitat for a regional fauna, rather than providing unique niches for new species.

The most abundant, widely distributed and largest of the gorgonians was *P. arborea*, and it exhibited a number of different phenotypes (white, pink and red color morphs, robust and delicate branches). Morphological differences were not genetically defined as all *Paragorgia* phenotypes collected were verified as *P. arborea* using mitochondrial gene sequencing (Clostio and France, in review). Color and branching structure variation also occurs in other species of deep corals; *L. pertusa* colonies may have heavily calcified or fragile branching patterns (Brooke and Schroeder 2007) and colonies from the eastern Atlantic often have orange pigmentation in their tissues. Coral pigments are created by different forms of carotenoids derived from diet (Elde et al. 2012) and can also be vertically transmitted through the eggs of pigmented colonies (Larsson et al. 2014). The purpose of these pigments has not been resolved definitively, but possibilities include anti-oxidant and antibiotic properties (Shnit-Orland et al 2008, Elde et al 2012) or they may confer a nutritional advantage (Neulinger et al. 2008). In the MAB canyons, all of the different *P. arborea* phenotypes were observed together with no clear distribution pattern; therefore, the selective benefits/costs of the different phenotypes are unclear and warrant further study. Other common octocoral species that usually co-occurred with *P. arborea* were *P. resedaeformis* and *A. grandiflora*, which had similar habitat associations and ranges of depth and environmental conditions.

Some species of octocorals were observed infrequently, but had very high local abundance; these included the gorgonian *P. placomus* and the soft coral *D. florida*. Most coral species were found on steep terrain with little or no sediment accumulation, but *P. placomus* was an exception. A single patch comprised of ~250 individuals was observed once in each canyon and

on both occasions the colonies were primarily distributed along the top of a flat rocky ledge with a sand veneer. The sediment layer was sufficiently thick in some places that the underlying hard substrate was invisible. Most corals cannot tolerate chronic high sediment environments, as particles can clog feeding and respiration apparatus (Reigl 1995, Kelmo et al 2003). Corals produce mucus in order to remove particles, and this energetically-expensive process cannot be sustained over long periods (Dallmeyer et al., 1982). Some species, such as *L. pertusa*, appear to have a moderately high tolerance to sediment (Brooke et al., 2009) and reduced oxygen levels (Dodds et al., 2007). Colonies of *P. placomus* can also evidently tolerate chronic suspended sediment and/or episodic high sediment deposition, which may allow them to exploit habitats that other species cannot. Flat sandy/rocky terraces were observed frequently in both canyons, but the very limited number of *P. placomus* observations implies the presence of a limiting factor (e.g., current speed, food, larval delivery) beyond habitat availability. The soft coral *D. florida* occurred in few locations but in extremely high numbers; they were observed in similar habitats to other octocorals, i.e., rocky boulders or walls so (as with *P. placomus*), it seems the distribution of *D. florida*, was also driven by factors other than habitat

Hexacorals (excluding anemones) were generally less abundant in both canyons than the octocorals, with two exceptions; a yellow *Parazoanthus* sp. that grows over dead (and possibly live) octocorals, and the cup coral *D. diathus*. Zoanthids were observed on *A. grandiflora*, *P. placomus* and *P. resedaeformis* (but not *P. arborea*). Yellow zoanthids overgrowing *P. placomus* were identified using sequence data as *Corallizoanthus* (Clostio and France, in review), but zoanthids collected from other octocorals were identified morphologically by J. Reimer as *Parazoanthus*. This taxon is currently being revised so this manuscript will use Reimer's ID, with the understanding that future revisions may classify this genus as

Corallizoanthus. The *Parazoanthus* sp. had often completely overgrown the ‘host’ octocoral skeleton, but it was also observed growing on partially-live colonies. It is not clear whether the zoanthids are parasitic on live colonies or merely taking advantage of dead skeleton as opportunistic substrate. These zoanthids were considerably more abundant in Norfolk Canyon than Baltimore Canyon. The abundance of *P. placomus* and *P. resedaeformis* was comparable between the two canyons, but there were more than twice as many *A. grandiflora* in Norfolk Canyon; therefore, the distribution of *Parazoanthus* sp. may be determined to some extent by the distribution of the ‘host’ species as well as the environmental tolerances of the zoanthid. The extremely high numbers of *D. dianthus* in Norfolk Canyon are driven by observations made during a single ROV dive (J2-685). A series of deep (~1200 m) vertical walls were heavily colonized by thousands of small *D. dianthus*, as well as *S. variabilis* and a putative new species of fileshell (*Acesta* nov. *cryptadelphe*, Gagnon et al. 2015). This extreme *D. dianthus* abundance was only observed on these deep walls of Norfolk Canyon where the individuals were small with fragile skeletons; however a moderately high abundance (~170) was also observed on a steep wall in Baltimore Canyon at ~670 m, but calices were much more robust. In shallower habitats (< 500 m), this species occurred on different types of rocky habitat, as large heavily calcified single specimens or in small clusters and was generally uncommon.

Environmental data used for correlations with coral distributions were collected during the ROV dives, and do not necessarily reflect long term conditions; however, since the dives occurred over a two week to one month period in two consecutive years and over a wide depth range, the data were considered useful for distributional analysis. While these correlative statistics are useful, they must be interpreted with caution and more work is needed to understand the causative relationships between environment and species distributions.

Coral abundances are most highly correlated with temperature and/or depth followed by pH, turbidity and oxygen. Depth and temperature have both been recognized as primary drivers of deep sea coral distributions (Roberts et al. 2009, Baker et al. 2012) so this is not a surprising outcome. Some species however, have a wide tolerance to temperature which could reduce the influence of temperature on their distribution. For example, *L. pertusa* can survive highly variable environments (Brooke et al. 2013) and has been observed in unusually warm conditions in the Mediterranean (Freiwald et al., 2009). Other research has indicated the importance of density to *L. pertusa* (Dullo et al 2008); in the northeastern Atlantic, living reefs were found between densities of 27.35 and 27.65 σ_θ , but *L. pertusa* colonies were observed in more dense waters (27.74-27.84 σ_θ) in Whittard Canyon, NE Atlantic (Huvenne et al 2011) and over a wider density range (27.32-28.23) in Baltimore and Norfolk canyons.

After depth and temperature, turbidity showed the highest correlation with coral abundance. Both of the canyons have periodically high turbidity levels, but Baltimore Canyon has a persistent dense nepheloid layer along the thalweg between 300-800 m depth (Davies et al, in review). This phenomenon was observed during ROV dives and was also reported during earlier work (Gardner, 1989), which adds support for a consistent pattern of mid-canyon turbidity maxima. In contrast, Norfolk has smaller, separate turbidity layers between 400-1100 m depth and a more uniform sediment deposition pattern (Davies et al. in review). There is ample evidence that high sediment loads have detrimental effects on stony corals, including reduced skeletal growth, reproductive capacity and lipid content as they shed sediment through the energetically costly processes of ciliary action and mucus production and in extreme cases, corals can suffocate under sediment load (Dallmeyer et al. 1982, Wesseling et al. 1999, Kelmo et al. 2003). Stony corals in the canyons were most frequently observed on steep walls or other

474 areas with little or no sediment accumulation, and there were many more stony corals observed
475 in Norfolk Canyon than Baltimore Canyon, especially *D. dianthus* and *S. variabilis* at the deeper
476 sites where turbidity is low (Fig. 11F). This distribution could reflect low stony coral tolerance to
477 sediment; however *L. pertusa* has shown high survival under chronic moderate sediment loads
478 and even short term burial (Brooke et al. 2009) so turbidity alone does not explain the observed
479 differences in stony coral abundance between the canyons, at least for *L. pertusa*.

480 Another notable difference in coral distribution between the canyons is the very high
481 abundance of *P. arborea*, in Baltimore Canyon (more than double the number observed in
482 Norfolk Canyon), which has a depth range that coincides with the nepheloid layer. The
483 gorgonian *P. placomus* was also found living in potentially high sediment environments on flat
484 pavements in both canyons. Some species can therefore tolerate high turbidity, and they may
485 even benefit from it nutritionally. Stable isotope studies have shown that deep corals living in
486 high sediment environments are consuming re-worked material such as older POM, whereas
487 those living in current swept conditions have access to fresher material and have a higher trophic
488 level (Sherwood et al. 2008). Generally in the deep sea, deposition of organic material decreases
489 with depth (Levin and Gooday 2003, Rex and Etter 2010); however, increased organic material
490 and high turbidity are characteristic of these features globally (Durrieu de Madron 1994, de
491 Stigter et al. 2007, Huvenne et al., 2011), and are important drivers of benthic communities
492 (Ingels et al. 2009; De Leo et al. 2010; Rex and Etter 2010).

493 As depth increases, Ω_{Arag} decreases (Feely et al. 2004), potentially making production of
494 calcified skeletons more energetically costly (Fabry 2008). Most of the corals in the current
495 study were found in $\Omega_{\text{Arag}} > 1.35$, which is within the currently known limits for deep sea corals
496 such as *L. pertusa* (Lunden et al 2012). The deepest dive off Norfolk Canyon (1257-1398) was

dominated by a steep wall, densely covered in thousands of small fragile *D. dianthus*. At this depth the Ω_{Arag} was ~ 1.2 and in shallower areas, where *D. dianthus* was heavily calcified ($\sim 400\text{--}700$ m), the Ω_{Arag} was ~ 1.5 ; however, it seems unlikely that this difference would explain the great differences in skeletal structure (particularly when both locations have $\Omega_{\text{Arag}} > 1$). Extreme high abundances have been observed elsewhere for this species (~ 1500 individuals/m² in the Chilean Fjords; Forsterra and Haussermann 2003) and in low Ω_{Arag} (Fillinger and Richter 2013). It seems therefore, that under certain circumstances *D. dianthus* shifts from small robust calices to very large numbers of fragile individuals. The reasons for this are not clear, but it is possible that the availability of large areas of good habitat (steep wall with little sedimentation) in the deep part of Norfolk Canyon allowed for high recruitment, but growth rates were reduced by other factors such as low temperatures, reduced food and competition for space. Differences in habitat availability and conditions between deep and shallower areas potentially create the different observed distributions and size structure in this species.

The deep coral reefs in the South Atlantic Bight (SAB) and Gulf of Mexico (GOM) are constructed by the stony corals *Lophelia pertusa* and *Enallopsammia profunda*, which can create large bioherms of consolidated coral rubble with live coral on the flanks and peaks. These deep reefs have a high diversity of gorgonians, antipatharians, sponges and other mobile and sessile invertebrates (Brooke and Schroeder 2007, Ross and Nizinski 2007). The deep corals that colonize the numerous seamounts and canyons of the northeastern US are primarily octocorals with some species of black corals and stony corals, but the overall coral species diversity is low (Packer et al 2007). The western Atlantic can be divided into two biogeographic provinces: the Warm Temperate Carolinian Province south of Cape Hatteras, NC and the Western Atlantic Boreal Region that extends from Cape Hatteras north to Labrador, Canada. There has, however,

been disagreement over the geographic extent of the boreal region as many of the fauna from the MAB belong to the southern Carolinian province. A recent realignment of marine biogeographic provinces based on fishes (Briggs and Bowen 2012) clearly places the MAB in the northern boreal region. The deep coral fauna from the canyons also more closely resembles those of the northeastern US, than the SAB. The three most frequently observed species of octocorals in the MAB are also common in the northeastern US but are either absent (*P. resedaeformis*, *A. grandiflora*) or very rare (*P. arborea*) in the SAB and GOM (Brooke and Schroeder 2007, Ross and Nizinski 2007). Other species such as *L. pertusa*, *S. variabilis* and *D. dianthus* have a broad distribution and are found throughout the North Atlantic. One exception is the gorgonian *Acanthogorgia aspera*, which was frequently observed in Norfolk Canyon. This species had not been documented north of Cape Hatteras prior to this study (Watling and Auster 2005; Clostio and France in review) so is more allied to the Carolinian province; the congener *A. armata* occurs in the northern boreal province.

Although the canyons are protected from fishing impacts to a great extent by their rugged topography, there was a significant amount of fishing gear (traps, lines, nets) observed in both natural and artificial habitats. In June 2015, the Mid Atlantic Fisheries Management Council (MAFMC) proposed to create a Deep Sea Coral Zones to protect an area of ~98,420 km² of vulnerable canyon and slope habitats to bottom-tending fishing gear. Data from this study and others (funded by NOAA DSCRTP and OER) provided data to assist the Council in generating boundaries for the protected areas. The MAFMC proposal is currently under consideration at the Department of Commerce, and once approved, will provide legislation to preserve these fragile and valuable resources. These data will also assist other U. S. Federal agencies in the management and conservation of these vulnerable ecosystems

543

544 **5. Conclusions**

545 The complexity of the physical and biotic conditions in the submarine canyons of the MAB has
546 generated a high diversity of fauna that does not occur on the shelf, particularly sessile benthic
547 fauna that colonize hard substrata. This study has greatly increased our understanding of the
548 distribution and abundance of deep-sea coral taxa in the MAB canyons, and as expected,
549 distributions are influenced by habitat type and environmental conditions, and consequently there
550 were also inter-canyon differences. Some species have a patchy distribution or are only found in
551 certain habitat types or depth ranges, whereas others are found in a wide range of habitats.
552 Although this study greatly increased our understanding of the corals and associated
553 communities of MAB canyons, these observations were limited by time and technical capability.
554 There are undoubtedly more coral species, and wider distributions of observed species, than were
555 encountered during this study, and further studies will reveal further interesting biological and
556 physical features of the MAB canyons. The application of this data to management and
557 conservation objectives highlights the value these studies beyond simply scientific
558 understanding.

559

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571

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814

815 **Figure Captions:**

816

817 **Figure 1.** Four of the major submarine canyons off the mid-Atlantic including Baltimore and
 818 Norfolk canyons which were the focus of this study. Shaded area represents coverage by
 819 multibeam sonar.

820

821 **Figure 2.** A-F Examples of different canyon habitat types A) S: Soft sediment with no hard
822 substrate visible (goosefish *Lophius americanus* is visible in the image), B) SR: Soft sediment
823 with small pieces of rock or emergent hard substrate (note cerianthid anemones and sponges) C)
824 R: Isolated rock, rubble > 50% cover of hard substrate D) PB: Large areas of hard substrate >50%
825 cover with attached sponges and anemones, E) B: Large boulder of rock or consolidated
826 sediment with attached octocorals and anemones, F) W: Walls and steep slopes

827

828 **Figure 3.** Images of octocorals observed in Baltimore and Norfolk canyons. A) *Paragorgia*
829 *arborea*, B) *Primnoa resedaeformis*, C) *Anthothela grandiflora*, D) *Paramuricea placomus* E)
830 Soft coral *Duva florida*, F) *Anthomastus* sp., G) *Acanthogorgia armata*, H) Bamboo coral
831 *Keratoisis cf grayi*, I) *Acanella arbuscula* and sea pen *Funiculina quadrangularis*

832

833 **Figure 4.** Images of hexacorals observed in Baltimore and Norfolk canyons A) *Lophelia*
834 *pertusa*, B) *Javania cf cailleti*, C) *Desmophyllum dianthus*, D) Zoanthids (*Parazoanthus* sp)
835 overgrowing dead octocoral skeleton, E) *Actinoschypia* sp., F) *Bolocera tunediae* G) Cerianthid
836 anemones, H) *Solenosmilia variabilis*, I) *Flabellum alabastrum*, J) *Telopathes magna*

837

838 **Figure 5.** Distribution of A) Baltimore Canyon octocorals, B) Baltimore Canyon hexacorals
839 observed during ROV dives

840

841 **Figure 6.** Distribution of A) Norfolk Canyon octocorals; B) Norfolk Canyon hexacorals
842 observed during ROV dives

843

844 **Figure 7.** Number of octocoral observations per hour of ROV transects in Baltimore and Norfolk

845 canyons

846

847 **Figure 8.** Number of hexacoral observations per hour of ROV transects in Baltimore and

848 Norfolk canyons

849

850 **Figure 9.** Multi-dimensional scaling plots on fourth root transformed coral abundance data using

851 a Bray-Curtis similarity matrix. A) by canyon B) by dive and C) by habitat type

852

853 **Figure 10.** PCA plot of environmental variables for all corals combined

854

855 **Figure 11.** Environmental data taken during ROV dives A) Temperature ($^{\circ}\text{C}$), B) Salinity, ($^{\circ}\text{C}$)

856 Density ($\sigma\theta$, kg m^{-3}), D) Dissolved oxygen (ml/L), E) pH, F) Turbidity (formazin turbidity units).

857 Water column data has been removed

858

859 **Figure 12.** Aragonite saturation state data for Baltimore and Norfolk canyons, compiled from

860 water samples taken during ROV dives and CTD casts

861

862 **Table Titles:**

863

864 **Table 1.** Codes used in habitat characterization for ROV dives conducted in Norfolk and

865 Baltimore canyons

866

867 **Table 2.** Number of observations (extracted from ROV video transects), depth range, habitat
868 type and environmental conditions associated with corals in A) Baltimore and B) Norfolk
869 canyons. See Table 1 for habitat type descriptions

870

871 **Table 3.** Correlations between environmental variables observed during ROV dives in both
872 canyons (Spearman rank correlation coefficients, ρ). Significant correlations * occurred between
873 temperature and both salinity and density.

874

875

Figure 1.

880 **Figure 2.**

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Figure 4.

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Figure 5.

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Figure 12.

Table 1.

Habitat Type	
S	Soft sediment with no hard substrate visible. Slope may be flat to steep.
SR	Soft sediment with small pieces of rock or emergent hard substrate (EHS). < 50% cover
R	Isolated rock, rubble, EHS. > 50% cover of hard substrate. Slope may be flat to steep
PB	Large areas of EHS or consolidated sediment that forms hard pavement. >50% cover of
B	Large boulder of rock or consolidated sediment. Slope may be flat to steep.
W	Walls and steep slopes (rock or consolidated sediment), steep profile
Percentage cover categories	
1	0
2	<25% cover
3	25-75% cover
4	>75% cover
Type of Structure Forming Cnidarians (SFC)	
LC	Large corals: <i>Paragorgia</i> , <i>Primnoa</i> , <i>Anthothela</i> , <i>Paramuricea</i> , <i>Lophelia</i> , <i>Solenosmilia</i>
LA	Large anemones and small corals: Cerianthids, <i>Actinoscyphia</i> , <i>Bolocera</i> , cup corals
M	Mix of TC and LA

Table 2.

A) Baltimore Canyon							
Species/Taxa	# Obs.	Depth (m)	Habitat types	Temp. (°C)	DO (ml/l)	pH	Turbidity
<i>Desmophyllum dianthus</i>	174	660-672	B, W	4.96-5.17	5.19-5.27	8.07-8.09	52.57-62.56
<i>Lophelia pertusa</i>	5	374-381	W	6.88-7.78	2.86-2.95	8.04-8.05	55.37-55.62
<i>Solenosmilia variabilis</i>	0						
<i>Antipathidae</i>	0						
<i>Parazoanthidae</i>	169	334-448	R, PB, B, W	5.69-9.88	2.46-4.90	8.00-8.07	22.51-90.14
<i>Acanthogorgia aspera</i>	0						
<i>Anthothela grandiflora</i>	571	320-672	PB, B, W	5.02-9.91	1.76-5.30	7.94-8.09	22.51-110.90
<i>Duva florida</i>	1,078	288-396	R, PB, B, W	5.80-11.16	2.24-4.84	8.00-8.10	14.57-90.67
<i>Keratoisis cf grayi</i>	3	428-447	W	6.73-7.27	4.11-4.43	7.96-8.03	27.47
<i>Paragorgia arborea</i>	5,697	331-793	R, PB, B, W	4.86-10.26	1.99-5.08	7.96-8.10	22.51-227.97
<i>Paramuricea placomus</i>	281	306-559	SR, R, W	6.37-9.51	3.73-4.91	8.03-8.08	52.87-144.81
B) Norfolk Canyon							
Species/Taxa	# Obs.	Depth (m)	Habitat types	Temp. (°C)	DO (ml/l)	pH	Turbidity
<i>Desmophyllum dianthus</i>	34,314	417-1390	R, PB, B, W	4.10-8.63	2.95-5.32	8.06-8.15	3.85-192.15
<i>Lophelia pertusa</i>	19	386-424	W	6.39-8.49	2.60-2.83	7.97-8.11	14.42- 65.39
<i>Solenosmilia variabilis</i>	306	1264-1388	B, W	4.10-4.29	2.13-4.41	8.11-8.12	3.85-11.10
<i>Antipathidae</i>	9	956-1339	SR, B, W	4.15	4.11	8.11	174.14
<i>Parazoanthidae</i>	531	384-1326	SR, R, PB, B, W	4.12-10.51	2.10-4.45	8.05-8.13	9.08-291.56
<i>Acanthogorgia aspera</i>	1,340	422-1341	SR, R, PB, B, W	4.10-6.67	2.55-5.30	8.05-8.12	3.85-192.15
<i>Anthothela grandiflora</i>	1,709	385-714	R, B, W	4.96-9.09	2.07-5.09	8.04-8.15	11.14-192.15
<i>Duva florida</i>	3,370	416-522	R, B, W	5.22-8.65	2.11-5.09	8.06-8.11	18.92-291.56
<i>Keratoisis cf grayi</i>	9	421-1223	SR, R, B, W	4.10-7.51	No data	No data	No data
<i>Paragorgia arborea</i>	2,166	383-716	SR, R, PB, B, W	4.94-11.41	2.07-5.32	8.04-8.15	10.38-219.23
<i>Paramuricea placomus</i>	256	421-460	PB, W	6.65-6.87	2.38-3.54	8.09-8.11	16.18-45.47
<i>Primnoa resedaeformis</i>	1,641	387-683	R, B, W	4.94-10.91	2.06-4.66	8.04-8.15	12.7-192.15

Table 3.

	Depth (m)	Temp. (°C)	Salinity	O₂ (ml/L)	pH	Density
Temp. (°C)	-0.6628					
Salinity	-0.5526	0.9494*				
O₂ (ml/L)	0.2835	-0.6960	-0.6484			
pH	0.4331	-0.3346	-0.2684	-0.1284		
Density	0.64672	-0.9889*	-0.9011	0.6795	0.3390	
Turbidity (FTU)	-0.2740	-0.1876	-0.2059	0.5106	-0.2830	0.1895