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Baseline

Microplastics and POPs on the Southwestern Atlantic deep-sea floor: a study of megafauna and sediments

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ABSTRACT

The deep sea is a historical sink for litter, but efforts to assess the human footprint in this ecosystem are relatively recent. Building upon previous works on the continental margins of the Southern Hemisphere, this study presents the first report of microplastics (MPs) and persistent organic pollutants (POPs) for the Southwestern Atlantic deep-sea floor. Ingestion of MPs by benthic invertebrates, and contamination by polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs) in demersal teleostean fish and sediments were recorded in the central Santos Basin, along the Brazilian continental slope, between 400 and 1503 m depth. Individuals from 9 invertebrate species ($n = 61$ organisms) had their gut content examined, with 3 species ingesting anthropogenic particles shaped like fibers ($n = 23$ fibers). The sea cucumber *Deima validum* was the most contaminated species, with 1.64 ± 0.70 fiber individual^{-1}, and 54.54 % of individuals ingesting fibers. Five fibers were identified as MPs, composed of polyamide, polyacrylonitrile, polyaryletherketone, polystyrene and polysulfide synthetic rubber. Total PCBs in the fish ($n = 14$ organisms) ranged from 519 to 7636 ng g^{-1} (lipid weight), and from 1.28 to 3.96 ng g^{-1} (dry weight) in the sediments. Among the PBDEs investigated, only BDE-47 and BDE-99 were found, and only in the fish. While additional work is needed to ascertain the possible origin and ecological implications of MPs and POPs found at the bottom of the ocean, this study provides critical data on pollution levels for the deep-sea community of Southeastern Brazil.

The deep sea is no stranger to human waste (see Woodall et al., 2014; Chiba et al., 2018). Between the dumping of burnt coal from steamships at the height of the Industrial Revolution and the worldwide ban on overboard littering in the 1970s (post London Convention), the "out of sight, out of mind" approach to waste disposal at sea has introduced mining refuse, pharmaceuticals, and even radioactive material to the seafloor (Ramirez-Llodra et al., 2011).

Plastics have become the most prominent example of pollutants which continually enter the ocean through urban runoff (Frias et al., 2014) and illegal dumping (Law et al., 2020). Upon reaching the ocean's surface, microplastics (MPs) – particles smaller than 5 mm in their longest dimension (GESAMP, 2019) – may be incorporated into marine snow or subjected to biofouling, turbidity currents and storms (Kooi et al., 2017; Kane et al., 2020; Chen et al., 2025), thus becoming negatively buoyant. Once MPs eventually sink to the deep sea, they may be ingested by bottom-dwelling organisms (Taylor et al., 2016). Persistent organic pollutants (POPs) are also fated to reach the bottom of the sea by means of contaminated sinking detritus and food falls, as well as seabed mining, ship traffic and accidental spills (Sanganyado et al., 2021). Given their low solubility and high affinity for carbon-rich particles, most organic pollutants also accumulate in biota (Lawson et al., 2021; Nakajima et al., 2022) and/or undergo adsorption onto the

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sediment (Zhang et al., 2020).

Studies focusing on the presence of pollutants in deep waters have become more abundant over the past decade, but there are still many information gaps pertaining to such environments in the Southern Hemisphere (Gage and Tyler, 1991). The first records of deep-sea litter in the Southwest Atlantic were recently obtained by Masumoto et al. (2023), revealing a considerable number of anthropogenic materials deposited on the continental slope. Likewise, levels of deep-sea MPs for the Southwest Atlantic are currently restricted to northeastern Brazil, found in mesopelagic cephalopods and fish (Ferreira et al., 2022, 2023; Justino et al., 2022). Nevertheless, our still growing knowledge of the biodiversity and vulnerability of the deep-sea environments within the

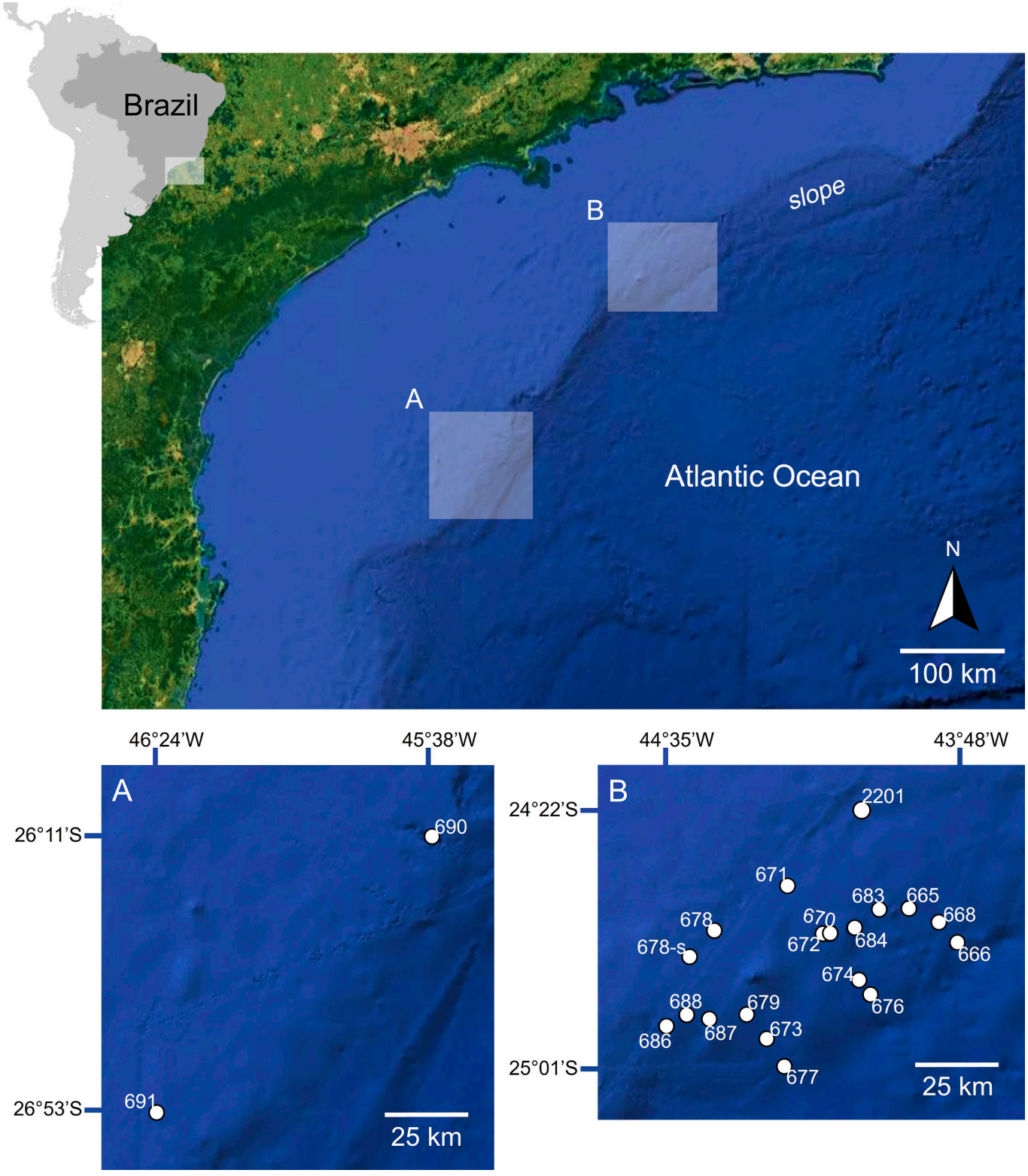

Fig. 1. Map depicting the two areas (A and B) surveyed in the central Santos Basin in September and November 2019, along the southwestern Brazilian continental slope, aboard the RV Alpha Crucis. White circles and numbers indicate sampling stations. Sampling stations are detailed in Table S1.

Brazilian continental margin contrasts with the high interests on the oil and mineral resources they supply, in addition to ecosystem services such as food provision and climate regulation, calling for more intense and high-quality research efforts (Bernardino and Sumida, 2017; Sumida et al., 2020).

Due to the importance of establishing preliminary levels of anthropogenic pollution in the South Atlantic (Melo et al., 2020), the objectives of the present study were to assess the occurrence and composition of MPs and two classes of POPs, i.e. polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs), in the megafauna and sediments of the Brazilian continental slope.

The study region encompasses two areas within the central Santos Basin, along the southern Brazilian continental slope (Fig. 1, Table S1). Sampling depth varied between 393 and 1503 m. Megafauna (i.e. organisms >10 mm in total length/diameter) was collected via bottom trawling, and sediment collection (top 10 cm layer) was carried out via a box corer (OSIL/Ocean Instruments; area of 0.25 m^2). Samples were secured in an aluminum bucket and wrapped in pre-muffled aluminum foil/containers (550 °C, 5 h) before being frozen at −20 °C. Collection took place aboard the RV Alpha Crucis as part of the projects DEEP-OCEAN (Diversidade E Evolução de Peixes de Oceano Profundo) and BIOIL (Biology and Geochemistry of Oil and Gas Seepages, SW Atlantic) in September and November 2019, respectively.

From all combined bottom trawls, 61 invertebrates belonging to 9 benthic and epibenthic species and 14 teleostean fish belonging to 8 demersal species were identified and analyzed (Table 1, Fig. 2). Invertebrates were either echinoderms ($n = 51$ individuals) or crustaceans ($n = 10$). Dominant feeding modes were determined according to the literature. When information was unavailable, the feeding mode was inferred based on records from either the same species found elsewhere, or evidence from congeneric species.

Back on land, an assessment of MP ingestion was carried out after invertebrate samples thawed out. Only invertebrates were used for this analysis. Organisms were rinsed with ultrapure water (Thermo Scientific Barnstead Easypure II), placed on a clean glass Petri dish, and then photographed and weighed using a precision scale (Shimadzu UX620H). The whole gastrointestinal tract (or central disk content in the case of asteroids) was carefully removed from each specimen. Before dissection of the gut content began, each sample was checked for particles floating around the isolated organ, which was then analyzed under a stereomicroscope (Nikon SMZ-1B).

Given the possibility of contamination during capture, handling and storage of samples, only intact specimens were considered in this analysis, i.e. all surveyed specimens had fully preserved outer body walls and wholly intact guts. This procedure was employed to reduce the possibility of ingestion/egestion of fibers after collection, to provide a snapshot of the environmental conditions at the time of sampling. All particles found within the gut content were photographed and placed on Anodisc membranes (Whatman; 25 mm in diameter, pore size of 0.02 μm) individualized in clean Petri dishes.

Quality assurance and control protocols for each work session followed Woodall et al. (2015). To minimize contamination, samples were handled in an isolated laboratory. During analysis, the air conditioner was turned off, and all doors and windows remained shut. All surfaces

Table 1
Deep-sea megafauna sampled during the DEEP-OCEAN cruise to the central Santos Basin in September 2019, along the southwestern Brazilian continental slope. Taxa are Class: Family for invertebrates and Order: Family for fish species. Sampling stations are detailed in Table S1. PCBs = polychlorinated biphenyls; PBDEs = polybrominated diphenyl ethers.

	Classification	Species	Station	Depth (m)	Samples (n)	Analyzed for
Invertebrates	Asteroidea: Astropectinidae	*Astropecten* sp. Gray, 1840	2201	400	1	Microplastics
			679	782–794	1	Microplastics
			674	1188–1220	1	Microplastics
	Asteroidea: Goniasteridae	*Ceramaster* sp. Verrill, 1899	673	1180–1190	1	Microplastics
	Asteroidea: Goniasteridae	*Nymphaster arenatus* (Perrier, 1881)	679	782–794	2	Microplastics
			665	944–1000	5	Microplastics
			668	1142	4	Microplastics
			673	1180–1190	13	Microplastics
			674	1188–1220	6	Microplastics
			676	1337–1342	2	Microplastics
			666	1367–1408	2	Microplastics
			677	1495–1503	2	Microplastics
	Holothuroidea: Deimatidae	*Deima validum* Théel, 1879	668	1142	3	Microplastics
			673	1180–1190	1	Microplastics
			674	1188–1220	2	Microplastics
			676	1337–1342	2	Microplastics
			666	1367–1408	1	Microplastics
			677	1495–1503	2	Microplastics
	Malacostraca: Aristeidae	*Aristaeopsis edwardsiana* (Johnson, 1868)	670	650–655	1	Microplastics
			679	782–794	1	Microplastics
	Malacostraca: Calappidae	*Acanthocarpus alexandri* Stimpson, 1871	678	393–400	1	Microplastics
			2201	400	1	Microplastics
	Malacostraca: Epialtidae	*Rochinia* sp. Milne-Edwards, 1875	2201	400	1	Microplastics
	Malacostraca: Geryonidae	*Chaceon ramosae* Manning, Tavares & Albuquerque, 1989	671	500	1	Microplastics
			670	650–655	1	Microplastics
	Malacostraca: Polychelidae	*Pentacheles validus* Milne-Edwards, 1880	679	782–794	1	Microplastics
			674	1188–1220	1	Microplastics
			677	1495–1503	1	Microplastics
Fish	Aulopiformes: Chlorophthalmidae	*Parasudis truculenta* (Goode & Bean, 1896)	678	393–400	1	PCBs and PBDEs
	Beryciformes: Trachichthyidae	*Hoplostethus occidentalis* Woods, 1973	671	500	1	PCBs and PBDEs
	Gadiformes: Macrouridae	*Coelorinchus marinii* Hubbs, 1934	671	500	2	PCBs and PBDEs
	Myctophiformes: Neoscopelidae	*Neoscopelus macrolepidotus* Johnson, 1863	672	720–737	1	PCBs and PBDEs
			679	782–794	2	PCBs and PBDEs
	Ophidiiformes: Ophidiidae	*Monomitopus americanus* (Nielsen, 1971)	679	782–794	2	PCBs and PBDEs
	Polymixiiformes: Polymixiidae	*Polymixia carmenae* Caixeta, Oliveira & Melo, 2024	671	500	1	PCBs and PBDEs
	Scombriformes: Trichiuridae	*Lepidopus altifrons* Parin & Collette, 1993	670	650–655	2	PCBs and PBDEs
			672	720–737	1	PCBs and PBDEs
	Zeiformes: Oreosomatidae	*Allocyttus verrucosus* (Gilchrist, 1906)	668	1142	1	PCBs and PBDEs

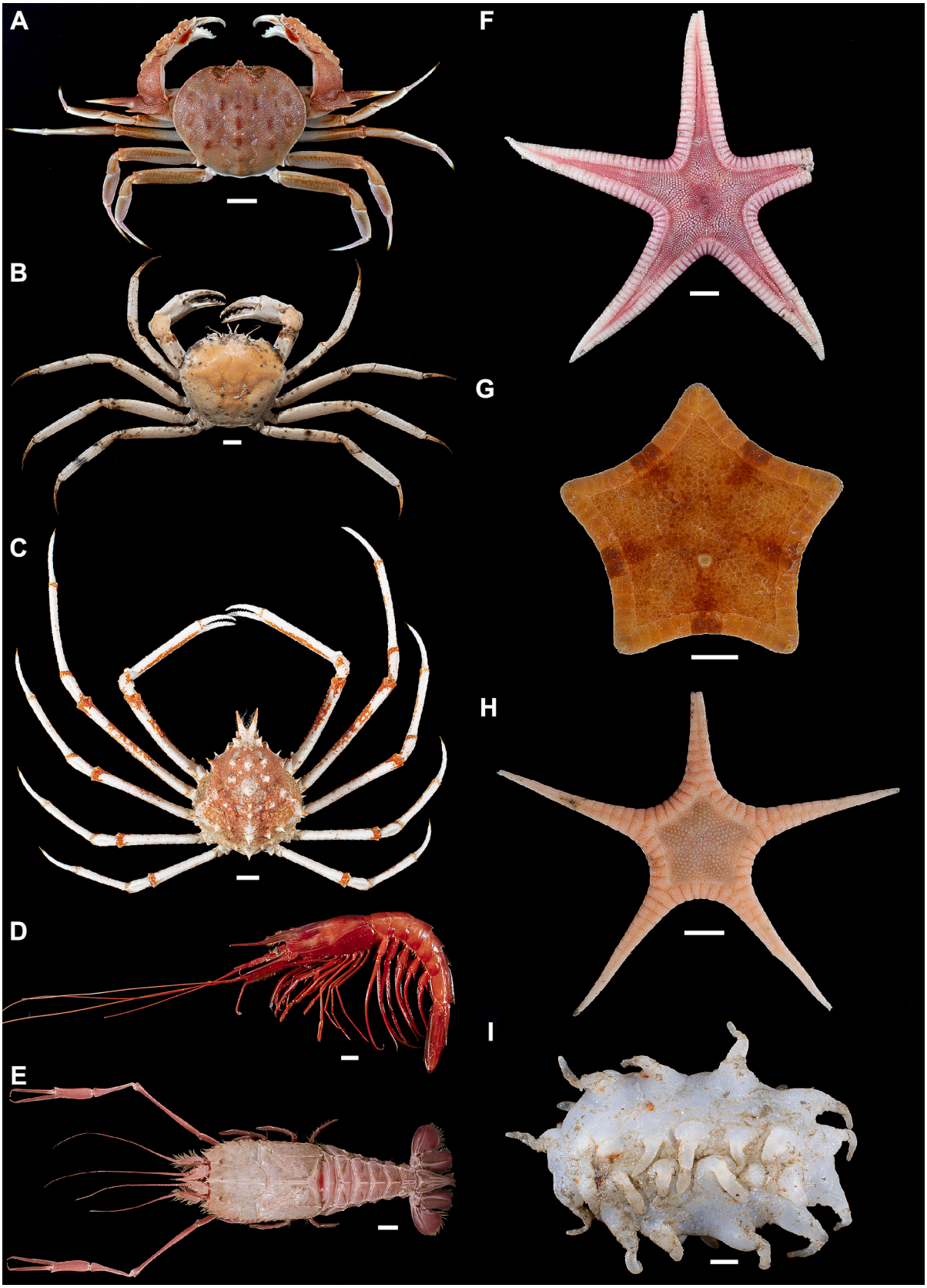

Fig. 2. Deep-sea megafauna comprised of invertebrates (above) and teleostean fish (next page) sampled during the DEEP-OCEAN cruise to the central Santos Basin in September 2019, along the southwestern Brazilian continental slope. Invertebrates: A. *Acanthocarpus alexandri*. B. *Chaceon ramosae*. C. *Rochinia* sp. D. *Aristaeopsis edwardsiana*. E. *Pentacheles validus*. F. *Astropecten* sp. G. *Ceramaster* sp. H. *Nymphaster arenatus*. I. *Deima validum*. Fish: A. *Allocyttus verrucosus*. B. *Coelorinchus marinii*. C. *Hoplostethus occidentalis*. D. *Lepidopus altifrons*. E. *Monomitopus americanus*. F. *Neoscopelus macrolepidotus*. G. *Parasudis truculenta*. H. *Polymixia carmenae*. Images are for illustrative purposes. The scale bar indicates 1 cm. All pictures by MRSM.

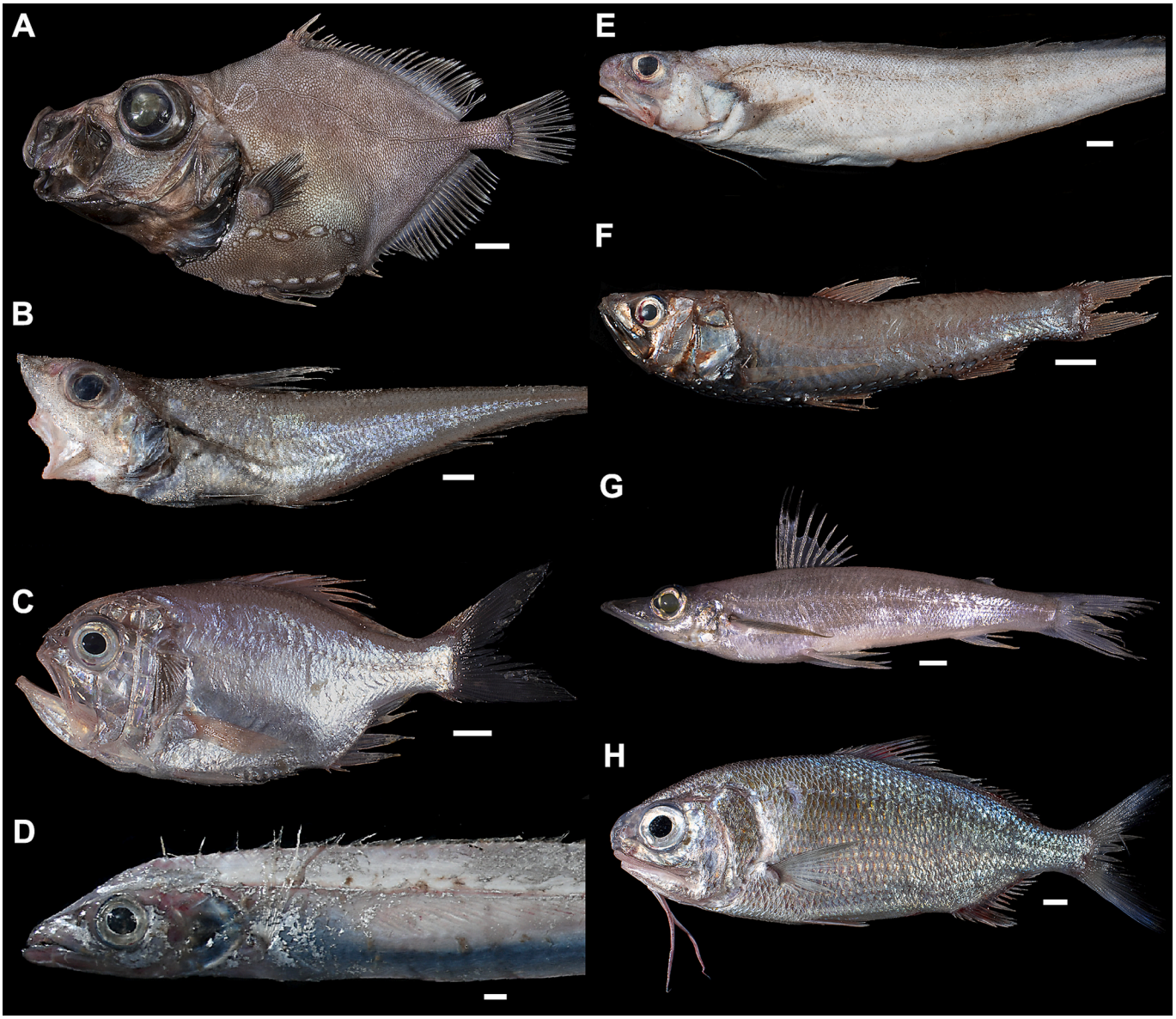

Fig. 2. (*continued*).

on the worktable were cleaned with filtered (100 μm) 70 % ethanol on nonshredding paper, three times prior to analysis. Natural fiber clothes were worn under a clean cotton laboratory coat which never left the laboratory. Whenever possible, metal and glass instruments were used in favor of plastic utensils. All instruments were thoroughly rinsed with ultrapure water prior to being used, and samples remained covered by a clean Petri dish whenever necessary to limit air exposure.

Tape lift screenings were employed to check for background MP particles on the table's surface before each work session: following ethanol cleanup, three pieces of clean adhesive tape (5 cm × 4 cm) were randomly adhered to the table and then carefully removed and adhered to a clean Petri dish, to be examined under the stereomicroscope. Blanks consisted of a fiberglass filter (Whatman; 47 mm in diameter, pore size of 0.7 μm) dampened with ultrapure water and placed in a clean Petri dish during each work session to check for airborne contamination. Filters were confirmed to be clean prior to and after being dampened. Likewise, any particles found were kept for further analysis. Finally, contamination was normalized by subtracting MP candidates that shared similar characteristics (i.e. shape, color or polymer) to particles found in the background controls and blanks, from every corresponding batch of samples processed on that day.

MP identification was performed via a LabRAM HR Evolution Raman microscope (HORIBA) with varying laser wavelengths (473 nm, 532 nm, 633 nm, and 785 nm) and a 50× long-range objective lens (NA = 0.55) (Bereczki et al., 2023). The resistance of particles to each laser type was tested so as not to damage samples, and laser wavelength and power were optimized accordingly, as well as integration time, number of accumulations, slit diameter and detector sensitivity. After optimization, the detector was checked for saturation over the entire spectral collection width, and signals were obtained within 1–3 min. A filter was employed to identify and automatically remove eventual spikes. An additional filter and a baseline correction algorithm were applied via LabSpec 6 (HORIBA) and MATLAB 9.13.0 (The MathWorks Inc, 2022). Raman spectra were identified using the KnowItAll database (Wiley Science Solutions) with a minimum similarity index of 60 %, excluding artifact regions.

For the analysis of POPs, fish and sediments were freeze-dried, and a sample of muscle tissue (approximately 10 g per individual) was obtained. No invertebrates were used for this analysis. The POP extraction and analysis protocol was adapted from MacLeod et al. (1985), the

United Nations Environment Programme (1992) and Combi et al. (2013). Muscle samples were further desiccated with sodium sulphate and then homogenized and ground with a mortar and pestle. Muscle (1 g) and sediment (10 g) samples were then extracted in a Soxhlet apparatus with a 50 % *v*/v hexane-dichloromethane mixture for 8 h. Solvent purity followed the requirement for "organic residue analysis" by Panreac Química S.L.U. Before the extraction, 100 μl of a mixture containing CB-103 and CB-198 surrogate standards (1 ng μl^{-1}) were added to the blanks, samples and reference material for the muscle and sediment samples (organics in whale blubber NIST SRM 1945 and organics in marine sediments NIST SRM 1941b, respectively).

For the muscle samples, the evaporated extract was cleaned up using a chromatography column containing 8 g of silica gel over 16 g of alumina (both Merck), 5 % deactivated with pre-extracted water (five times) eluted with n-hexane, and 1 g of sodium sulphate (J. T. Baker) on top. Elution was achieved with an 80 ml mixture of n-hexane and dichloromethane (50 %). For further purification, the eluate was concentrated to 0.9 ml and injected in a liquid chromatograph (Agilent Technologies) equipped with two exclusion columns (gel permeation). Dichloromethane was used as the mobile phase. The eluate was further concentrated, and a tetrachloro-m-xylene standard was added. The final volume was 1 ml. Similarly, for the sediment samples, the extract was purified in a glass chromatography column containing 3.2 g of deactivated alumina (5 %) where PCBs and PBDEs were eluted with a 20 ml mixture of dichloromethane in n-hexane (30 % *v*/v).

For both muscle and sediment samples, an aliquot of the final extract was injected in a gas chromatograph equipped with a triple quadrupole mass spectrometer (GC/MS/MS) (7890/7010B, Agilent Technologies). GC/MS/MS temperatures in the injector, interface and ion source were maintained at 300 °C. A 30 m × 0.25 mm (film thickness of 0.25 μm) HP-5ms ultra inert (5 %-phenyl)-methylpolysiloxane column (Agilent J&W) was used. Multiple reaction monitoring (MRM) was used as the mode of acquisition. The oven temperature started at 50 °C for 1 min, increasing at a rate of 20 °C up to 200 °C, and a rate of 10 °C up to 300 °C, remaining constant for 5 min.

Quantification was performed via the ratio between surrogates and compounds of interest, based on the analytical curves following reference standards (AccuStandard). The following compounds were investigated: CBs- (IUPAC No.) 8, 18, 28, 31, 33, 44, 49, 52, 56/60, 66, 70, 74, 77, 81, 87, 95, 97, 99, 101, 105, 110, 114, 118, 123, 126, 128/167, 132, 138, 141, 149, 151, 153, 156, 157, 158, 169, 170, 174, 177, 180, 183, 187, 189, 194, 195, 199, 203, 206 and 209, including the ICES (International Council for Exploration of the Sea) 7 PCB congeners (CBs- 28, 52, 101, 118, 138, 153 and 180), and BDEs- (IUPAC No.) 28, 47, 99, 100, 153, 154 and 183.

As a result of the analysis of MPs pertaining to the 9 invertebrate species, 39 particles were found within their gut content; all fibers. These were classified as blue ($n = 20$; ~51 % of total), black ($n = 13$; 33 %), red (n = 2; ~5 %), green (n = 2; ~5 %), blue and white (n = 1; ~3 %) and white (n = 1; ~3 %). As for the background particles, 20 particles were found via the dampened filter blanks ($n = 15$; 0.66 ± 0.18 fiber day^{-1}) and tape lift screenings ($n = 4$; 0.19 ± 0.08 fiber day^{-1}); also all fibers. Background fibers were classified as blue ($n = 11$; 55 %), black (n = 4; 20 %), green ($n = 3$; 15 %), red and white (n = 1; 5 %), and blue and white (n = 1; 5 %).

Of the total 59 fibers, 27 were subjected to Raman spectroscopy: 5 fibers were composed of plastic or plastic and cellulose/rayon blend, 1 was composed of a nonplastic polymer, 2 were composed of cellulose/rayon and the remaining fibers – including all background fibers – did not produce usable polymeric data or only yielded dye spectra. Plastic polymers were identified as polyamide (PA), polyaryletherketone (PAEK), polyacrylonitrile (PAN), polystyrene (PS) and polysulfide synthetic rubber. Poly(sodium 4-styrenesulfonate) (PSS) was identified as a non-plastic synthetic polymer. Fibers of the same color found in both the invertebrates and the blanks/control screenings within the same day of processing were excluded. Following this conservative approach, 16 fibers were removed from this study.

In all, 23 fibers were considered as having been ingested by the invertebrates (Table 2). Eleven individuals ingested at least a single fiber, resulting in an ingestion rate of 18.03 % and average ingestion of 0.37 ± 0.15 fiber $individual^{-1}$ across all invertebrate specimens. Fibers ranged from 0.26 to 1.77 mm in length.

Fibers classified as MPs were found in five individuals (Table S2), among which three were the sea cucumber *Deima validum*, and two were the sea star *Nymphaster arenatus*. Polymers in *D. validum* were identified as PAN (blue fiber, 1.17 mm long), PS (green fiber, 0.89 mm long) and polysulfide synthetic rubber (black fiber, 1.00 mm long), and polymers in *N. arenatus* were identified as PA (blue fiber with cellulose blend, 1.12 mm long) and PAEK (blue fiber, 0.74 mm long) (Fig. S1). All MPs were found in individuals sampled between 1142 and 1503 m. Additionally, the plasticizer bis(2-ethylhexyl) adipate (known as DEHA) was identified in the PAEK fiber.

Eight of the nine invertebrates reported here are predators, although not exclusive. Five of these species were also identified as scavengers and one as a deposit feeder (Table S3; for a definition of the feeding modes, see Table S4). Only two predacious species (sea stars *Astropecten* sp. and *N. arenatus*) ingested fibers. Predators thus ingested 21.74 % of fibers. All remaining fibers (78.26 % of total), including the cellulose/rayon fibers, were found in *D. validum*, the only exclusive deposit feeder in this study. Likewise, fiber ingestion was highest in *D. validum*, with 1.64 ± 0.70 fiber $individual^{-1}$ and over half of individuals ingesting at least one fiber (Table 2).

In the fish muscle samples, total PCBs ranged from 519 to 7636 ng g^{-1} lw (lipid weight), and ICES 7 PCBs ranged from 174 to 2780 ng g^{-1} lw (Table S5). Tetra-PCBs and penta-PCBs were the main contributors to contamination across most species, except for *Hoplostethus occidentalis* where the concentration of tri- and tetra- chlorine substituents was higher (Fig. 3A). Regarding the sediment samples, total PCBs ranged from 1.28 to 3.96 ng g^{-1} (dry weight) (Table S6), with tri- and tetra-PCBs being the main contributors (Fig. 3B).

Among the PBDE congeners investigated, only BDE-47 (2,2′4,4′-tetrabromodiphenyl ether) and BDE-99 (2,2′,4,4′,5-pentabromodiphenyl ether) were found in the fish samples (Table S7). BDE-47 was found in *Lepidopus altifrons* and *Polymixia carmenae* at a concentration of 11.2 and 22.4 ng g^{-1} lw, respectively, and BDE-99 was present in *L. altifrons*, *Monomitopus americanus* and *H. occidentalis* at a concentration of 1.27, 5.69 and 20.7 ng g^{-1} lw, respectively. The same *L. altifrons* individual was contaminated with both PBDE congeners. The concentration of PBDEs was below the quantitation limit for the remaining fish specimens and across all sediment samples.

This is the first study to document the occurrence of MPs and POPs on the deep-sea floor of the Southwest Atlantic. The presence of these contaminants in an area over 140 km from the nearest coast is indicative of the potential for transport of MPs via ocean circulation, possibly through the bottom layer of the Brazil Current (Stramma, 1989) and the North Atlantic Deep Water (Zangenberg and Siedler, 1998). Likewise, PCBs and PBDEs originating from coastal industrial activity and dredged-up sediment in the Santos Bay (Buruaem et al., 2013) can reach the ocean basin via sewage outfall (Abessa et al., 2005) and atmospheric transport (reviewed by Sanganyado et al., 2021). Meanwhile, ingestion of anthropogenic fibers, especially by sediment dwellers, is a natural consequence of the ubiquitous prevalence of MPs along the seafloor, even in deep waters (Van Cauwenberghe et al., 2013).

The sea cucumber *D. validum* was the most contaminated species in terms of total fibers ingested and number of organisms which ingested fibers. Since holothurians are vulnerable to ingesting MPs in the sediment (Mohsen et al., 2019; Plee and Pomory, 2020) and may even selectively ingest MPs (Graham and Thompson, 2009; Renzi et al., 2018), these results are possibly related to the cucumber's deposit-feeding habit. However, the combined assessment of MPs in sediment as well as biological matrices is needed for conclusive evidence. While most species in this study are predacious, the ingestion of fibers was

Table 2
Fibers ingested by invertebrates sampled during the DEEP-OCEAN cruise to the central Santos Basin in September 2019, along the southwestern Brazilian continental slope. Fibers are presented in relation to corresponding species, species mass range, prevalent feeding mode, percentage of individuals which ingested at least one fiber, number of fibers ingested, fiber size range and color, number of fibers per individual, and corresponding sampling station. Sampling stations are detailed in Table S1.

Species (n)	Mass (g)	Feeding mode	Ingestion rate	Fibers ingested	Fiber length (mm)	Fiber color (n)	Fiber ind^{-1} (mean ± S.E.)	Station
Astropecten sp. (3)	18.55–44.7	Predation (Beddingfield and McClintock, 1993; Guilherme and Rosa, 2014)	33.33 %	1	0.41	Black	0.33 ± 0.33	2201
Deima validum (11)	4.65–90	Deposit-feeding (Alberic and Khripounoff, 1984)	54.54 %	18	0.26–1.51	Black (11), blue (4), green (2), red	1.64 ± 0.70	666, 668, 674, 676, 677
Nymphaster arenatus (36)	3.45–20.11	Predation (Wagstaff et al., 2014), scavenging (Costa et al., 2015; Mah, 2016)	11.11 %	4	0.52–1.77	Blue (3), red	0.11 ± 0.05	673, 677

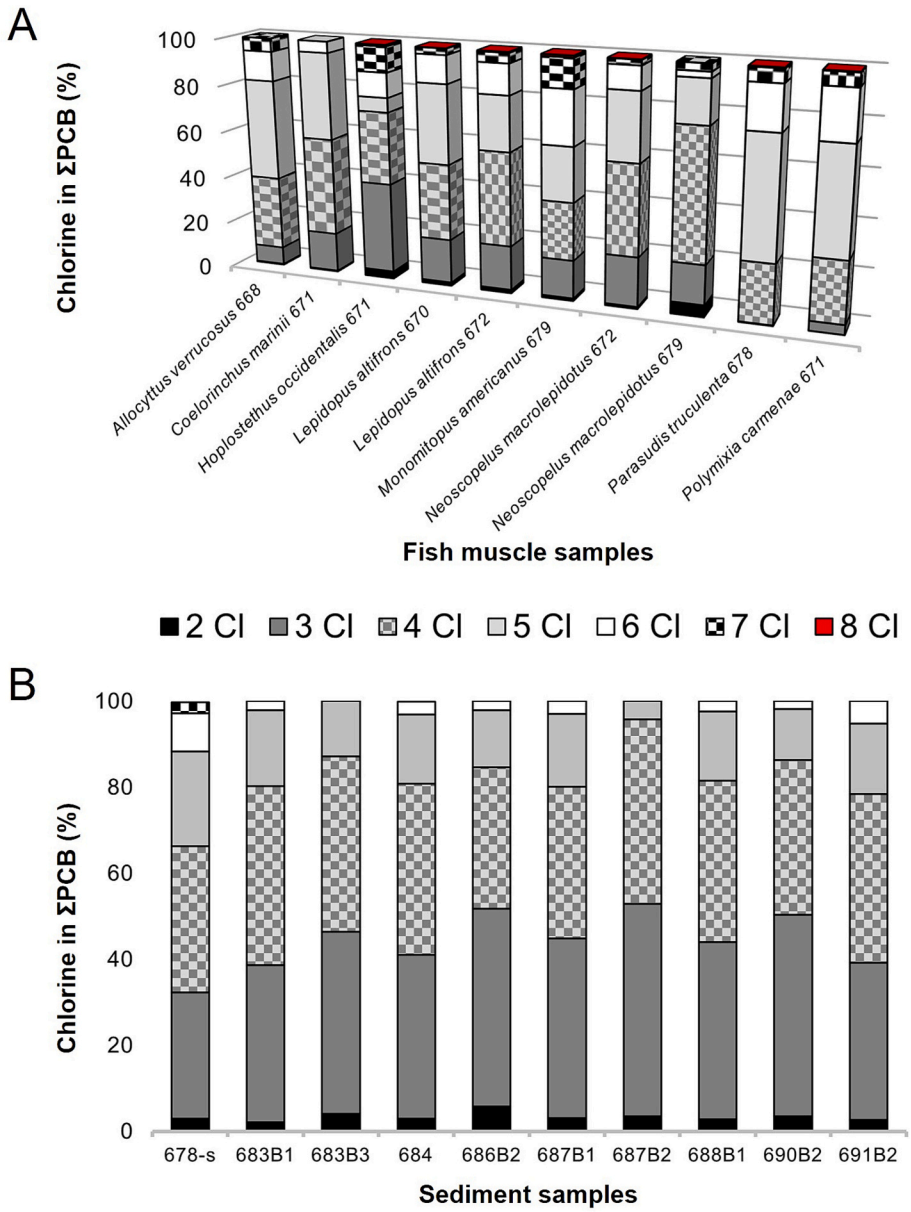

Fig. 3. Total polychlorinated biphenyls (PCBs) arranged by number of chlorine (%) in deep-sea samples obtained during the DEEP-OCEAN and BIOIL cruises to the central Santos Basin in September and November 2019, along the southwestern Brazilian continental slope. A. Fish muscle samples identified by species and station. B. Sediment samples identified by station. Sampling stations are detailed in Table S1. B# = box number.

considerably lower for such organisms, namely the sea stars *Astropecten* sp. and *N. arenatus*. Regardless of feeding mode, all specimens which ingested fibers were benthic echinoderms, which are more likely to encounter these particles while foraging. Indeed, the association between bottom-feeding and MP intake is well documented in marine organisms (Thompson et al., 2004; Wright et al., 2013; Zhang et al., 2020).

Currently, studies of MPs in deep-sea organisms from the Southwest Atlantic have been carried out for the vampire squid *Vampyroteuthis infernalis* Chun, 1903 (9.58 ± 8.25 MPs individual^{-1}) and the midwater squid *Abralia veranyi* (Rüppell, 1844) (2.37 ± 2.13 MPs individual^{-1}; Ferreira et al., 2022), myctophids (1.27 MP individual^{-1}; Ferreira et al., 2023), and a combination of myctophids and sternoptychids (1.25 MP individual^{-1}; Justino et al., 2022). For comparison's sake, the highest ingestion value for *D. validum* in the present study is over five times lower than for *V. infernalis*. Ferreira et al. (2022) argue that despite this cephalopod's pelagic foraging environment not being as contaminated by MPs, its feeding habit of actively selecting sinking aggregates could result in an increased intake of anthropogenic particles. While the differences in behavior and habitat between these organisms are not to be trivialized, this observation highlights the importance of ecological data (in this case, feeding mode) for assessing MP ingestion. Furthermore, it emphasizes the role of marine snow as a vector for MPs that ultimately reach the deep-sea floor.

When presenting baseline levels of MPs, especially in remote environments, it is important to stress potential limitations. The conservative approach chosen here for the MP analysis – i.e. subtracting similar fibers found in the blanks and control screenings – meant that over 40 % of fibers initially associated with the invertebrates were discarded to minimize the risks of background contamination. Additionally, since not all fibers could be chemically characterized, these findings may be an underestimation of actual environmental levels of MPs.

Regarding the polymers which could be characterized, polyamide and semisynthetic cellulose/rayon fibers are used in textile fabrics, while PS is commonly employed in packaging containers. Although it is not possible to determine the original purpose and source of the materials these particles came from, one can assume a domestic origin for most of these, as fibers are released from textile washing cycles (reviewed by Cesa et al., 2017) and can even undergo atmospheric transport (De Falco et al., 2020) across great distances. As for the PAEK, PAN and polysulfide rubber fibers, these materials are employed in the oil drilling, electronics and automotive industries, and can thus reach the deep-sea floor either through wastewater effluents or directly from offshore platforms (Osten et al., 2023). Five platforms currently operate in the Santos Basin and six more are to be implemented by 2027, with a prospective yield of over a million oil barrels per day (Petrobras, 2025).

The prevalence of lower-chlorinated PCBs (tetra- in fish; tri- and tetra- in sediments) in this study is indicative of an off-site source of contamination and long-range transport, as higher-chlorinated congeners are typically deposited close to the source (de Souza et al., 2018). Additionally, higher vapor pressure values in lower-chlorinated congeners also indicate a possible atmospheric transport for these compounds (Harvey and Steinhauer, 1974). BDE-47 and BDE-99, the only PBDE congeners found here, were also the only ones found in shallow-water fish in the nearby Baixada Santista coastal area (Magalhães et al., 2017). These are the main components of the pentabromodiphenyl ether commercial mixture, and both congeners display a greater bioavailability in relation to other PBDE components (De Wit, 2002).

This study offers a glimpse of MP and POP levels for the seafloor environment within the Southwest Atlantic, between 393 and 1503 m. The benthic sea cucumber *D. validum* is an especially promising indicator of MP pollution in the sediment, as its feeding ecology appears to facilitate the ingestion of fibers. The fate of the contaminants reported here is a direct consequence of the "out of sight, out of mind" approach to anthropogenic waste which has historically impacted the deep sea. Considering that results were based on a limited number of organisms, spread over one of multiple environments that make up the Santos Basin, additional monitoring efforts are needed to determine the human footprint in the region, across multiple feeding modes and trophic levels, and encompassing other contaminants. Lastly, studies on the proximity of offshore platforms could offer valuable information on possible leaks and the impacts of current and future oil drilling and mining projects.

CRediT authorship contribution statement

Gabriel Stefanelli-Silva: Investigation, Formal analysis, Conceptualization, Writing – review & editing, Writing – original draft. **Marcelo R.S. de Melo:** Project administration, Investigation, Funding acquisition, Writing – review & editing. **Diego R.C. Pascoal:** Formal analysis. **Jessica Dipold:** Formal analysis, Writing – review & editing. **Niklaus U. Wetter:** Funding acquisition, Writing – review & editing. **Anderson Z. Freitas:** Funding acquisition. **Satie Taniguchi:** Formal analysis, Writing – review & editing. **Rosalinda C. Montone:** Writing – review & editing. **Paulo Y.G. Sumida:** Supervision, Project administration, Funding acquisition, Conceptualization, Writing – review & editing.

Ethics statement

Collection permits were issued by the Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio; SISBio permits 28054-4 and 82624-1 to MRSM) and the Secretaria da Comissão Interministerial para Recursos do Mar da Marinha do Brasil (SECIRM; ordinance #223 to MRSM). Handling of vertebrates was approved by the Comitê de Ética em Uso de Animais em Pesquisa e Ensino do Instituto Oceanográfico da Universidade de São Paulo (CEUA; permits #8 to GS-S and #16 to MRSM).

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

GS-S reports financial support was provided by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior and the Fundação de Amparo à Pesquisa do Estado de São Paulo. PYGS reports financial support/equipment was provided by the Conselho Nacional de Desenvolvimento Científico e Tecnológico, Shell Brasil, and the Fundação de Amparo à Pesquisa do Estado de São Paulo. MRM reports financial support was provided by the Fundação de Amparo à Pesquisa do Estado de São Paulo and Marinha do Brasil. NUW reports financial support/equipment was provided by the Conselho Nacional de Desenvolvimento Científico e Tecnológico, the Fundação de Amparo à Pesquisa do Estado

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.119148.

Data availability

Data will be made available on request.

References

Abessa, D.M.S., Carr, R.S., Rachid, B.R.F., Sousa, E.C.P.M., Hortelani, M.A., Sarkis, J.E., 2005. Influence of a Brazilian sewage outfall on the toxicity and contamination of adjacent sediments. Mar. Pollut. Bull. 50, 875–885.
Alberic, P., Khripounoff, A., 1984. Relations entre les compositions en acides amines des particules en voie de sedimentation, du contenu intestinal des holothuries abyssales et du sediment environnant. Mar. Chem. 14 (4), 379–394.
Beddingfield, S.D., McClintock, J.B., 1993. Feeding behavior of the sea star *Astropecten articulatus* (Echinodermata: Asteroidea): an evaluation of energy-efficient foraging in a soft-bottom predator. Mar. Biol. 115, 669–676.
Bereczki, A., Dipold, J., Freitas, A.Z., Wetter, N.U., 2023. Sub-10 nm nanoparticle detection using multi-technique-based micro-raman spectroscopy. Polymers 15 (24), 4644.
Bernardino, A.F., Sumida, P.Y.G., 2017. Deep risks from offshore development. Science 358 (6361), 312.
Buruaem, L.M., de Castro, Í.B., Hortellani, M.A., Taniguchi, S., Fillmann, G., Sasaki, S.T., Petti, M.A.V., Sarkis, J.E.S., Bícego, M.C., Maranho, L.A., Davanso, M.B., Nonato, E. F., Cesar, A., Costa-Lotufo, L.A., Abessa, D.M.S., 2013. Integrated quality assessment of sediments from harbour areas in Santos-São Vicente Estuarine System, Southern Brazil. Estuar. Coast. Shelf Sci. 130, 179–189.
Cesa, F.S., Turra, A., Baruque-Ramos, J., 2017. Synthetic fibers as microplastics in the marine environment: a review from textile perspective with a focus on domestic washings. Sci. Total Environ. 598, 1116–1129.
Chen, P., Kane, I.A., Clare, M.A., Soutter, E.L., Mienis, F., Wogelius, R.A., Keavney, E., 2025. Direct evidence that microplastics are transported to the deep sea by turbidity currents. Environ. Sci. Technol. 59 (14), 7278–7287.
Chiba, S., Saito, H., Fletcher, R., Yogi, T., Kayo, M., Miyagi, S., Ogido, M., Fujikura, K., 2018. Human footprint in the abyss: 30 year records of deep-sea plastic debris. Mar. Policy 96, 204–212.
Combi, T., Taniguchi, S., de Lima Ferreira, P.A., Mansur, A.V., Figueira, R.C.L., Michaelovitch, M., Montone, R.C., Martins, C., 2013. Sources and temporal patterns of polychlorinated biphenyls around a large South American grain-shipping port (Paranaguá Estuarine System, Brazil). Arch. Environ. Contam. Toxicol. 64, 573–582.
Costa, P.A.S., Mincarone, M.M., Braga, A.C., Martins, A.S., Lavrado, H.P., Haimovici, M., Falcão, A.P.C., 2015. Megafaunal communities along a depth gradient on the tropical Brazilian continental margin. Mar. Biol. Res. 11 (10), 1053–1064.
De Falco, F., Cocca, M., Avella, M., Thompson, R.C., 2020. Microfiber release to water, via laundering, and to air, via everyday use: a comparison between polyester clothing with differing textile parameters. Environ. Sci. Technol. 54 (6), 3288–3296.
De Wit, C.A., 2002. An overview of brominated flame retardants in the environment. Chemosphere 46 (5), 583–624.
Ferreira, G.V., Justino, A.K., Eduardo, L.N., Lenoble, V., Fauvelle, V., Schmidt, N., Junior, T.V., Frédou, T., Lucena-Frédou, F., 2022. Plastic in the inferno: microplastic contamination in deep-sea cephalopods (*Vampyroteuthis infernalis* and *Abralia veranyi*) from the southwestern Atlantic. Mar. Pollut. Bull. 174, 113309.
Ferreira, G.V., Justino, A.K., Eduardo, L.N., Schmidt, N., Martins, J.R., Ménard, F., Fauvelle, V., Mincarone, M.M., Lucena-Frédou, F., 2023. Influencing factors for microplastic intake in abundant deep-sea lanternfishes (Myctophidae). Sci. Total Environ. 867, 161478.
Frias, J.P., Otero, V., Sobral, P., 2014. Evidence of microplastics in samples of zooplankton from Portuguese coastal waters. Mar. Environ. Res. 95, 89–95.
Gage, J.D., Tyler, P.A., 1991. Deep-Sea Biology: A Natural History of Organisms at the Deep-Sea Floor. Cambridge University Press, 520 p.
GESAMP, 2019. Guidelines or the monitoring and assessment of plastic litter and microplastics in the ocean. In: GESAMP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection. Reports and Studies, 99. GESAMP, 130 p.
Graham, E.R., Thompson, J.T., 2009. Deposit- and suspension-feeding sea cucumbers (Echinodermata) ingest plastic fragments. J. Exp. Mar. Biol. Ecol. 368 (1), 22–29.
Guilherme, P.D., Rosa, L.C., 2014. Seasonal variation in body size and diet of the sea star *Astropecten marginatus* (Paxillosida, Astropectinidae) off coast of Paraná, Southern Brazil. Rev. Biol. Trop. 62 (1), 73–83.
Harvey, G.R., Steinhauer, W.G., 1974. Atmospheric transport of polychlorobiphenyls to the North Atlantic. Atmos. Environ. (1967) 8 (8), 777–782.
Justino, A.K., Ferreira, G.V., Schmidt, N., Eduardo, L.N., Fauvelle, V., Lenoble, V., Sempéré, R., Panagiotopoulos, C., Mincarone, M.M., Frédou, T., Lucena-Frédou, F., 2022. The role of mesopelagic fishes as microplastics vectors across the deep-sea layers from the Southwestern Tropical Atlantic. Environ. Pollut. 300, 118988.
Kane, I.A., Clare, M.A., Miramontes, E., Wogelius, R., Rothwell, J.J., Garreau, P., Pohl, F., 2020. Seafloor microplastic hotspots controlled by deep-sea circulation. Science 368 (6495), 1140–1145.
Kooi, M., Nes, E.H., Scheffer, M., Koelmans, A.A., 2017. Ups and downs in the ocean: effects of biofouling on vertical transport of microplastics. Environ. Sci. Technol. 51 (14), 7963–7971.
Law, K.L., Starr, N., Siegler, T.R., Jambeck, J.R., Mallos, N.J., Leonard, G.H., 2020. The United States' contribution of plastic waste to land and ocean. Sci. Adv. 6 (44), eabd0288.
Lawson, M.C., Cullen, J.A., Nunnally, C.C., Rowe, G.T., Hala, D.N., 2021. PAH and PCB body-burdens in epibenthic deep-sea invertebrates from the northern Gulf of Mexico. Mar. Pollut. Bull. 162, 111825.
MacLeod, W.D., Brown, D.W., Friedman, A.J., Burrows, D.G., Maynes, O., Pearce, R.W., Wigren, C.A., Bogar, R.G., 1985. NOAA Tech. Memo NMFS F/NWC-92. Standard Analytical Procedures of the NOAA National Analytical Facility, 1985–1986. Extractable Toxic Organic Components. U. S. Department of Commerce, 121 p.
Magalhães, C.A., Taniguchi, S., Lourenço, R.A., Montone, R.C., 2017. Organochlorine pesticides, PCBs, and PBDEs in liver and muscle tissues of *Paralonchurus brasiliensis*, *Trichiurus lepturus* and *Cathorops spixii* in Santos Bay and surrounding area, São Paulo, Brazil. Reg. Stud. Mar. Sci. 16, 42–48.
Mah, C.L., 2016. Deep-sea (> 1000 m) Goniasteridae (Valvatida; Asteroidea) from the North Pacific, including an overview of *Sibogaster*, *Bathyceramaster* n. gen. and three new species. Zootaxa 4175 (2), 101–141.
Masumoto, F.T., Gomes, A.A., de França, R.D., de Melo, M.R., 2023. First report of deep-sea litter on the Brazilian continental slope, southwestern Atlantic. Mar. Pollut. Bull. 197, 115717.
Melo, M.R.S., Caires, R.A., Sutton, T.T., 2020. The scientific explorations for deep-sea fishes in Brazil: the known knowns, the known unknowns, and the unknown unknowns. In: Sumida, P.Y.G., Bernardino, A.F., De Léo, F.C. (Eds.), Brazilian Deep-Sea Biodiversity. Springer, pp. 153–216.
Mohsen, M., Wang, Q., Zhang, L., Sun, L., Lin, C., Yang, H., 2019. Microplastic ingestion by the farmed sea cucumber *Apostichopus japonicus* in China. Environ. Pollut. 245, 1071–1078.
Nakajima, R., Kawato, M., Fujiwara, Y., Tsuchida, S., Ritchie, H., Fujikura, K., 2022. Occurrence and levels of polybrominated diphenyl ethers (PBDEs) in deep-sea sharks from Suruga Bay, Japan. Mar. Pollut. Bull. 176, 113427.
Osten, J.R., Benítez-Torres, J.A., Rojas-González, R.I., Morgado, F., Borges-Ramírez, M. M., 2023. Microplastics in sediments from the southern Gulf of Mexico: abundance, distribution, composition, and adhered pollutants. Sci. Total Environ. 873, 162290.
Plee, T.A., Pomory, C.M., 2020. Microplastics in sandy environments in the Florida keys and the panhandle of Florida, and the ingestion by sea cucumbers (Echinodermata: Holothuroidea) and sand dollars (Echinodermata: Echinoidea). Mar. Pollut. Bull. 158, 111437.
Ramirez-Llodra, E., Tyler, P.A., Baker, M.C., Bergstad, O.A., Clark, M.R., Escobar, E., Levin, L.A., Menot, L., Rowden, A.A., Smith, C.R., Van Dover, C.L., 2011. Man and the last great wilderness: human impact on the deep sea. PLoS One 6 (8), e22588.
Renzi, M., Blašković, A., Bernardi, G., Russo, G.F., 2018. Plastic litter transfer from sediments towards marine trophic webs: a case study on holothurians. Mar. Pollut. Bull. 135, 376–385.
Sanganyado, E., Chingono, K.E., Gwenzi, W., Chaukura, N., Liu, W., 2021. Organic pollutants in deep sea: occurrence, fate, and ecological implications. Water Res. 15 (205), 117658.
de Souza, A.C., Taniguchi, S., Figueira, R.C., Montone, R.C., Bícego, M.C., Martins, C.C., 2018. Historical records and spatial distribution of high hazard PCBs levels in sediments around a large South American industrial coastal area (Santos Estuary, Brazil). J. Hazard. Mater. 360, 428–435.
Stramma, L., 1989. The Brazil current transport south of 23° S. Deep Sea Res. Part A 36 (4), 639–646.
Sumida, P.Y.G., Bernardino, A.F., De Léo, F.C., 2020. Brazilian Deep-Sea Biodiversity. Springer, 284 p.
Taylor, M.L., Gwinnett, C., Robinson, L.F., Woodall, L.C., 2016. Plastic microfibre ingestion by deep-sea organisms. Sci. Rep. 6 (1), 33997.
The MathWorks Inc, 2022. MATLAB version: 9.13.0 (R2022b), Natick, Massachusetts.

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 304 (5672), 838.
United Nations Environment Programme, 1992. Determinations of petroleum hydrocarbons in sediment. In: Reference Methods for Marine Pollution Studies n. 20, 75 p.
Van Cauwenberghe, L., Vanreusel, A., Mees, J., Janssen, C.R., 2013. Microplastic pollution in deep-sea sediments. Environ. Pollut. 182, 495–499.
Wagstaff, M.C., Howell, K.L., Bett, B.J., Billett, D.S., Brault, S., Stuart, C.T., Rex, M.A., 2014. β-diversity of deep-sea holothurians and asteroids along a bathymetric gradient (NE Atlantic). Mar. Ecol. Prog. Ser. 4 (508), 177–185.
Woodall, L.C., Sanchez-Vidal, A., Canals, M., Paterson, G.L., Coppock, R., Sleight, V., Calafat, A., Rogers, A.D., Narayanaswamy, B.E., Thompson, R.C., 2014. The deep sea is a major sink for microplastic debris. R. Soc. Open Sci. 1 (4), 140317.
Woodall, L.C., Gwinnett, C., Packer, M., Thompson, R.C., Robinson, L.F., Paterson, G.L., 2015. Using a forensic science approach to minimize environmental contamination and to identify microfibres in marine sediments. Mar. Pollut. Bull. 95 (1), 40–46.
Wright, S.L., Rowe, D., Thompson, R.C., Galloway, T.S., 2013. Microplastic ingestion decreases energy reserves in marine worms. Curr. Biol. 23 (23), R1031–R1033.
Zangenberg, N., Siedler, G., 1998. Path of the North Atlantic deep water in the Brazil Basin. J. Geophys. Res. Oceans 103 (C3), 5419–5428.
Zhang, D., Liu, X., Huang, W., Li, J., Wang, C., Zhang, D., Zhang, C., 2020. Microplastic pollution in deep-sea sediments and organisms of the Western Pacific Ocean. Environ. Pollut. 259, 113948.

Web reference

Petrobras, 2025. Explore ultra-deep waters on a 7,000-meter dive and discover all about the pre-salt. https://petrobras.com.br/en/pre-sal#2000m. Accessed on August 4, 2025.