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Letter

Large Plastic Debris Dumps: New Biodiversity Hot Spots Emerging on the Deep-Sea Floor

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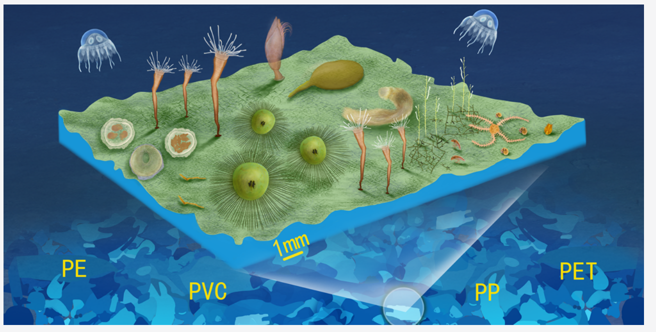
ABSTRACT: Macroplastic debris recorded in the Mariana Trench and accumulated on some deep-sea canyons worldwide has aroused great public concerns. Large plastic debris dumps found in canyons of the Xisha Trough, South China Sea have become hot spots for deep-sea pollution, with 1 order of magnitude higher abundance than in other investigated canyons. Here we adopted an integrative specimen-based approach to examine macroplastic items from large debris dumps in the Xisha Trough and comparative items from continental shelves with rare macroplastics. On the investigated items, we found an epibenthic ecosystem with relatively high species diversity, comprised of 49 mm-sized fungi and invertebrate species dominated by scyphozoan polyps and brachiopod juveniles according to inhabiting density. These large dumps are functioning as new biodiversity hot spots hosting endemic species like soft corals or aplacophoran molluscs, providing a spawning habitat for gastropods and even specialized parasitic flatworms, and can be inferred as potential scattered regional sources releasing deep-sea coronate jellyfish. We hypothesize that macroplastics can boost population extension of sessile and some free-living (Mollusca) invertebrates and affect the deep-sea benthic-pelagic coupling process. The baseline of associated organisms needs to be set up and monitored in more canyons, where debris is transported to and accumulated at the highest density.



INTRODUCTION

Marine plastic debris is a major environmental issue[1−3] that even threatens the polar and deep-sea floors where host exceptional levels of invertebrate endemism and diversity.[4−7] Some buoyant plastics are considered to quickly accumulate organic coatings, absorb sand and other debris, and sink to the seabed due to an increase in bulk density.[8] Macroplastic objects of low specific gravity sink and amass on the sea bed, accounting for 80−85% of the seabed debris.[9] Due to sophisticated technical and logistic challenges and prohibitive research costs of deep-sea research, macroplastics on the deep-sea floor have not received much attention until recently.[10−17] During the recent deepest manned sea-dive recorded in the Mariana Trench (10,927 m), macroplastics were found in the deepest region of the trench by the lander *Triton*.[18] In addition, and for the first time, large plastic debris dumps patchily piled up on the deep-sea floor were recorded by the manned submersible *Shenhaiyongshi* at ∼1700−3200 m in submarine canyons of the Xisha Trough, South China Sea.[19,20] The marine debris is dominated by macroplastic objects, and its abundance is up to 51,929 items/km^2 which is 1 order of magnitude higher than in other investigated submarine canyons.[20]

Unlike the well-known direct negative threats of macroplastics, i.e., inhibitive effect on gas exchange between sediment layers, entanglement of marine mammals, and ingestion by marine organisms,[8,10] a boosting effect of macroplastics in supplying additional habitats for colonization of organisms has been widely considered in shallow waters. Macroplastics were reported to supply habitats for colonization to opportunistic sessile invertebrates, including epibionts, encrusters, and fouling and associated biota.[8,21] For example, abundant sessile macroalgae and invertebrates and even molluscan egg masses were found to colonize or to be spawned on macroplastics on the coastline of Svalbard in the Arctic Ocean.[22] Several sessile crustaceans and bryozoans were reported to disperse remotely by colonization on macroplastics in the South Pacific.[23] More than 50% of the litter items (mainly consisting of macroplastics) in the Mediterranean Gulf of Naples were colonized by diverse invertebrates including reproductive structures such as molluscan egg masses.[24] Sea anemones were commonly found

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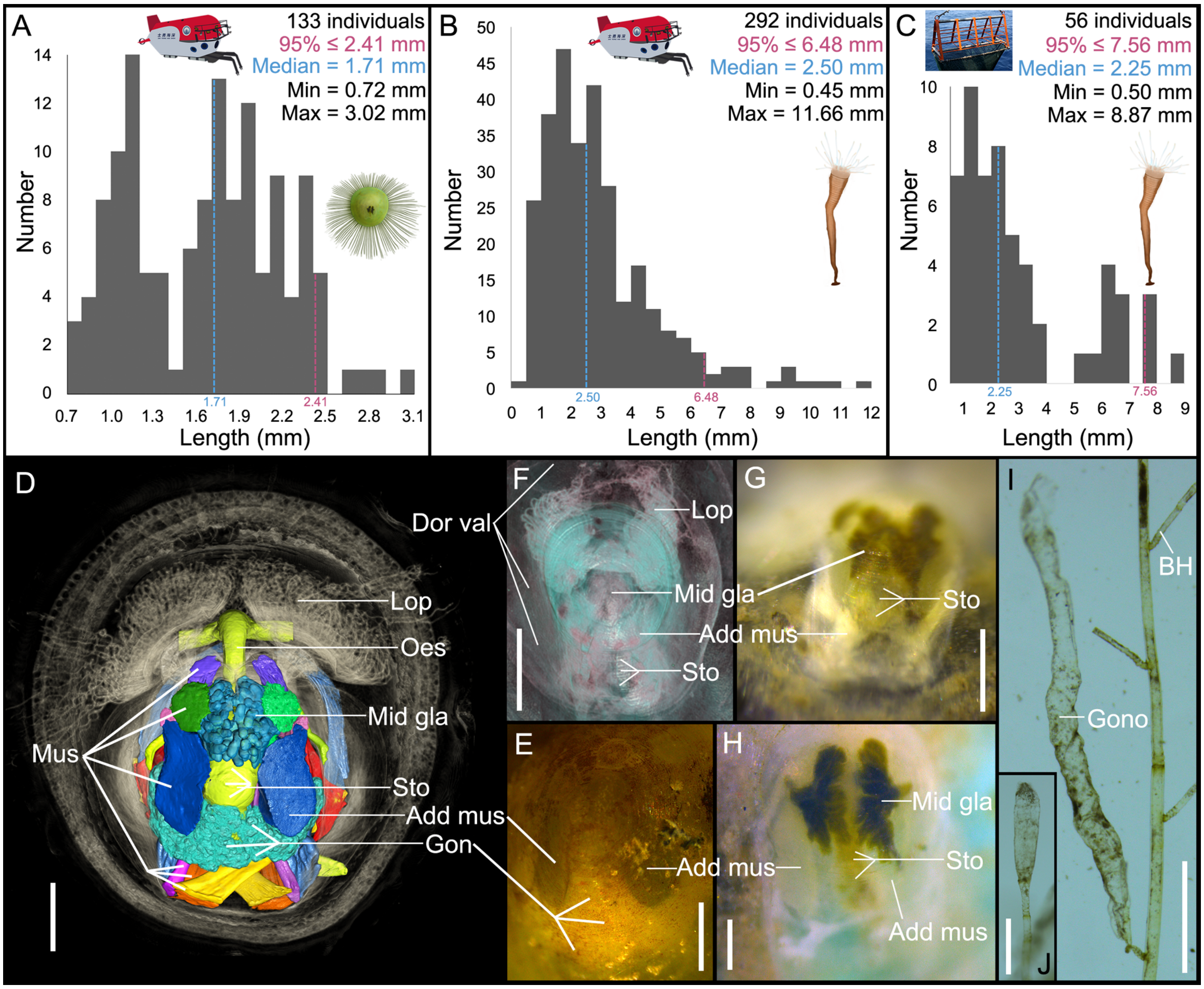

Figure 1. Individual measurement and sexual maturity determination for the dominant species inhabiting macroplastics on the deep-sea floor in the South China Sea. (A−C) Statistics of the length of all investigated individuals of the brachiopod *Pelagodiscus atlanticus* (A) and scyphozoan chitinous periderm tubes (B, C); specimens were collected by a submersible from large plastic debris dumps on submarine canyons in the Xisha Trough (A, B) or from flat bottoms of the continental shelves by dredging (200−300 km to the nearest shore, C). (D−H) Sexual maturity comparisons for a mature individual from natural habitat (gravel, nonmacroplastics, XMUB6035, D, E) and the two largest juveniles on macroplastics (XMUB7380, F, G; XMUB7010, H) based on micro-CT 3D visualization (D, F) and light microscopy (E, G, H); the reproductive gonad is present in the reference mature individual (D, E) but absent in both juveniles (F−H). (I, J) Hydroid colonies of *Campanulina* sp. 2 with one reproductive gonotheca; (J) indicates a hydrotheca, XMUB7700. Annotations: Mus, muscles; Add mus, main adductor muscles; Lop, lophophore; Oes, esophagus; Mid gla, midgut gland; Sto, stomach; Gon, gonad; Dor val, Dorsal valve (transparant); Gono, Gonotheca; BH, basal part of the hydrotheca. Scale bars: D, E, I = 1 mm; F, G, J = 500 μm; H = 200 μm.

attached to macroplastics on the coastal seabed of the Yellow Sea.[25]

Observations by underwater videos or photographs revealed marine organisms such as large sponges, corals, and sea anemones inhabiting macroplastic debris on the deep-sea floor.[10−17] However, further close examinations based on specimens are required, particularly for certain minute macrobenthos organisms, to understand the ecological interactions. In some pioneer cases of objects collected from the bottom, the polyps of a blooming jellyfish *Aurelia limbta* were first found on a macroplastic via bottom dredging at depths of 296 and 392 m in Japan;[26] deep-sea corals and barnacles were recorded on rafting floats in the central Mediterranean Sea.[27] Minute sponges, hydroids, and bryozoans were discovered growing on a single fishing rope item that entangled the research ROVs (Remotely Operated Vehicles) at the depth of 700 m on the Blanes canyon, northwestern Mediterranean Sea.[28] The safety of the ROVs is the biggest challenge during the collection of deep-sea debris samples.[28] The lack of more detailed investigation of organisms on the debris might be also due to the easy disregard of the small organisms.

Here we present insight into the epibenthic communities on abundant deep-sea macroplastic items collected by the manned submersible *Shenhaiyongshi* (including all nine previous[19,20] and new dives from the large plastic debris dumps in the Xisha Trough) or bottom dredging in the South China Sea. For identifying the macroplastic associated organisms, an integrative taxonomic approach is adopted, including the sophisticated micro-CT technology and life history analyses. The impact of macroplastics on the deep-sea benthic community is discussed, and several policy relevant conservation practices are suggested.

■ MATERIALS AND METHODS

Thirty-three macroplastic items (carrying nearly 1,200 epibenthic benthos individuals) were collected from the deep-sea floor (820−3,233 m) of the South China Sea, by nine manned submersible dives and from four comparative bottom dredging stations (Table S1 and Figures S1−S3) within the last three years. The organisms were investigated by adopting an integrative approach that combined light and scanning electron microscopy (SEM), micro-CT 3D, DNA barcoding, biogeography, and life history analyses (Tables S1−S7 and Figures S4−S6). Morphological and molecular data contributed by this study have been deposited in GenBank and MorphoBank (morphobank.org/permalink/?P3840), respectively. Additional methods are supplied in the Supporting Information Section S1.

■ RESULTS AND DISCUSSION

Characters of Investigated Plastic Items. According to underwater video, macroplastic objects (plastic bags, woven bags, capped plastic bottles, and plastic food wrappers) were the most prevalent debris in the Xisha Trough region, followed by derelict fishing gear including ropes, fishing lines, and shrimp traps.[20] The 33 plastic items for detailed examination cover most of these types (Figure S2). The maximum, median, and minimum surface area of the examined items is 172 dm^2, 5.9 dm^2, and 0.02 dm^2, respectively. The chemical composition of these macroplastics was mostly polyethylene (PE, 27 items), followed by polypropylene (PP, three items), polyvinyl chloride (PVC, one item), and polyethylene terephthalate (PET, one item). The coating layer of the pop-top can is comprised of PET and PVC. The general appearance, measurement, and chemical composition of all items are given in detail in Table S1 and Figures S2 and S3. The known density of the abundant buoyant PE and PP plastic ranges from 0.85 to 0.97 g/mL,[29] and their densities have increased in seawater likely due to absorbing debris[8] and biofouling.[29] We simply tested this using several small plastic pieces cut from the Item 7 (PE). After having been cleaned, these plastic pieces became buoyant in water again.

Epibenthic Ecosystem Inhabiting Deep-Sea Macroplastics. The identification of the taxa to the species, genus, or higher taxonomic level is given in the Supporting Information S1 and Tables S1−S4. The epibenthic ecosystem we found on macroplastics is comprised of 49 species belonging to 11 phyla, including 26 sessile (e.g., fungi, scyphozoan polyps, hydroids, black corals, barnacles) and 23 free-living species (e.g., polycheates, echinoderms) inhabiting the thin sedimental layers on the macroplastics. In total, 32 species were recorded from the submersible samples, and 25 species were recorded from the dredging samples. There were eight species even inhabiting one dredged small bottle (Item 21). Some free-living organisms selected macroplastics as a temporary substratum for reproduction. Egg capsules attached to macroplastics by four gastropod species and a breeding cocoon of a flatworm generally parasitizing crustaceans were found. Altogether this seems to be high organism diversity.

The total biological density on the macroplastic surface is 1.33 ind/dm^2 and 14.13 ind/dm^2 for the submersible and dredging samples, respectively (Table S4). The higher density of the dredging samples from continent shelves is partially attributable to the accumulation of benthic foraminifera on four items. On the large debris dumps, the most abundant group/species are the scyphozoan polyps and the brachiopod *Pelagodiscus atlanticus*. These brachiopods were only recorded on plastics from the submersible sample.

The body length of the organisms examined ranges from 0.4 mm to 25 mm. Only a few fungi and hydrozoan colonies or individuals of the aplacophorans, bivalves, and polychaetes are over 10 mm in length (Table S1). The length of 95% individuals of the dominant scyphozoans and brachiopods is lower than 2.41 mm and 7.56 mm, respectively (Figure 1A−C). The only unambiguously recognized mature material found is represented by the hydroid *Campanulina* sp. 2; it carried several well-developed gonothecae (Figure 1I). Early colonies of several sponges, soft corals, hydroids, and juvenile bivalves and echinoderms were easily determined. The combination of microscopic and micro-CT observations showed that the gonad is missing in all individuals in the dominant brachiopod group (133 *P. atlanticus* and one *Gwynia* sp.). These brachiopods settling on the macroplastic sheets in the large debris dumps are juveniles and do not contribute to reproduction/population extension. We assume that these nonmobile brachiopods become detached and die when reaching a certain size, because the attachment to the plastic surface becomes insufficient. This may also depend on the type and the thickness of the plastic substratum. According to the estimation by growth rings,[30] the age of most investigated *P. atlanticus* individuals is no more than one and a half years (body length: 95% ≤ 2.41 mm, Figure 1A); the largest individual (Figure 1A, F, G) inhabited the plastic for about two years. Another explanation for the absence of mature brachiopod specimens is that the duration for these specific plastic objects since settlement was too short.

Population Extension and Connectivity of Sessile Organisms on Macroplastics. The deep-sea sessile benthos presented in this work (Table S3) and elswhere[10−15] colonizing on macroplastics are composed of fungi and a wide range of invertebrates, including at least 12 phyla: Ciliophora, Foraminifera, Porifera, Cnidaria, Platyhelminthes (cocoons), Annelida, Brachiopoda, Mollusca, Arthropoda, Bryozoa, Echinodermata, and Chordata. Most of these groups have two-phase life cycles, with pelagic larval (or medusa) and benthic adult (or polyp) stages. Additional substratum affects the larval supply and recruitment as well as the benthic-pelagic coupling processes of sessile invertebrates and pelagic medusa.[26,31,32] Such effects might lead to a decrease in the food supply and oxygen availability and alterations in the population structures of other free-living benthic groups.[31] A clear change in the community composition of the epibenthic megafauna after artificial placement of plastic bottles has been demonstrated for shallow water.[33] It could be hypothesized that the large plastic debris dumps in Xisha Trough might boost population extension of certain invertebrates and thus affect the composition of deep-sea endemic biodiversity.

Morphological data indicate a biological connectivity between debris dumps of different canyons in the Xisha Trough for the scyphozoan *Atorella sibogae* (stations SY085 and SY083, geographic distance 84 km) and the barnacle *Weltnerium* sp. (stations SY083 and SY227, 114 km). Long geographic biological connectivity in *A. sibogae* was also detected between the debris dump in the Xisha Trough and a rare plastic bottle collected in flat continental shelves (Stations SY083, SY085, and St1, 1430−1460 km). Molecular 28S rRNA data support connectivity (3900 km in straight-line distance) in the abundant

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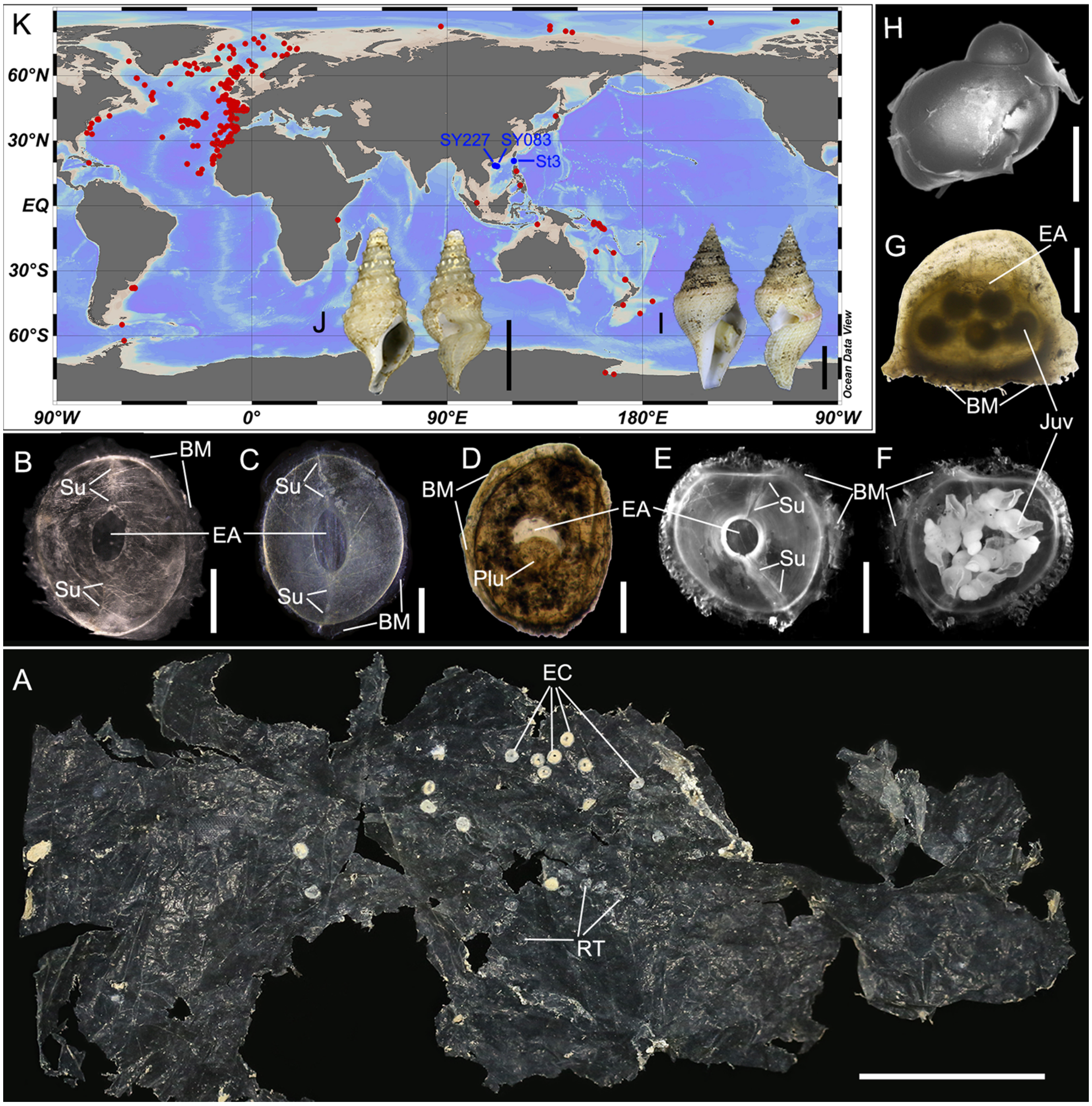

Figure 2. Gastropod egg capsules on plastic and biogeography of deep-sea gastropods with direct development (releasing crawling juveniles). (A−D) Egg capsules spawned by two gastropods on macroplastic sheets, see the magnified map for stations in Figure S1. (A, B) Dredging from flat bottoms of Luzon Strait where recorded macroplastics are rare. (C, D) Manned submersible sample from large plastic debris dumps on submarine canyons in Xisha Trough. (A−C) Neogastropoda sp. 1, Item 24 (A), XMUB6513 (B), St3, 2,359 m; Item 15, XMUB7618 (C), SY227, 1,900 m. (D) Neogastropoda sp. 2, a smaller egg capsule on item 5, XMUB7614, SY083, 2807 m. (E, F) Comparative capsules of the shallow-water gastropod *Coronium coronatum* prior to (F) and after (E) the release of juveniles. (G, H) Comparative capsules of *Penion* sp. with unhatched juveniles from the deep sea of the Antarctic. (I, J) Potential parents of the capsules, *Bathytoma* sp. (I) and *Leucosyrinx luzonica* (J). (K) Biogeography of deep-sea gastropod records with direct development. Annotations: EA, escape aperture; Su, suture; BM, basal membrane; Juv, juvenile; Plu, plug for the escape aperture; EC, egg capsules; RT, remaining trace. Scale bars: A = 3 cm; B, C = 1 mm; D = 200 μm; E, F = 5 mm; G = 2 mm; H = 500 μm; I, J = 1 cm.

brachiopod *P. atlantic* between the South China Sea (on debris dumps) and the Micronesia (on natural habitat, unpublished data), Western Pacific Ocean.

The Usage of Macroplastics by Endemic Species with a Direct Development Pattern. Direct development is reported to be the dominant larval pattern in deep-sea invertebrates,[34] including mollusks.[35−37] Two mollusk species recorded on several plastic sheets are most likely direct developers (Supporting Information Section S2). A literature review (Table S7) indicates that this development type is common at all depth ranges of oceans worldwide, and it was reported in deep-sea gastropods worldwide belonging to at least 137 species in 33 families and 86 genera (Table S7 and Figure 2K). Direct developers have limited dispersal abilities, and many of them are endemic to specific conditions or small habitats.[38] Therefore, these organisms might be sensitive to the presence of additional plastic substrates during reproduction and egg-laying. It is premature to evaluate properties such as the steadiness and surface condition of the plastic pieces for long-term intracapsular development because the encapsulated development duration of certain cold-water gastropods can be quite long, e.g., up to two years for several deep-sea Antarctic gastropods (*Neobuccinum*

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eatoni: 15 months; *Torellia mirabilis* and *Trophon* cf. *scotianus*: 24−25 months).[39] The encapsulated development of an Antarctic shallow-water gastropod *Antarctodomus thielei* was reported as taking up to eight years.[40]

Large Plastic Debris Dumps as New Biodiversity Hot Spots. Hydrothermal vents, cold seeps, and whale falls are well-known natural biodiversity hot spots on the deep-sea floor. These hot spots support a high-biomass benthic community driven by chemoautotrophic bacterial production[41] or the decomposition of whale carcasses.[42] This suggests the community on macroplastics should also be fueled by the descent of the low biomass of the surface primary production, as observed in general deep-sea sediments inhabiting small invertebrates.[41] Obviously, the large plastic debris dumps accumulated in deep-sea submarine canyons are special hot spots for environmental pollution reflecting anthropogenic activities. Nevertheless, they are also biodiversity hot spots for benthic organisms.

This may be illustrated by some of our findings. First, some endemic macrobenthos species, e.g., three deep-sea cold-water corals (Figure S4E) and two aplacophoran molluscs (spicule "worms", Figure S4O, P), were found in debris dumps; four gastropod species (Figure 2A−D) and one flatworm parasitizing crustaceans (Figure S4I) spawned egg capsules or secreted breeding cocoons on macroplastic sheets. Second, some deep-sea species known on the basis of only a few samples could be easily sampled in a considerable number from macroplastics, e.g., *Attorella sibogae*. Abundant macroplastic samples might even lead to the discovery of new species. The hydroid *Campanulina* sp. 2 we found is morphologically and genetically different from known species. It may eventually be described as a species new to science. Third, the large debris dumps also provide additional shelter or help to mimick deep-water caves for some larger organisms like fishes. Two rockfish were found to use a shoe and a tire as caves in the deep-sea floor of Monterey Canyon.[15] Benthic fish were also observed around the debris dump in Xisha Trough.[20] At last, the large debris dumps in the Xisha Trough dominated by coronate polyps may function as reproductive hot spots for the coronate jellyfish to release ephyras and could be of great importance for the regional benthic-pelagic coupling process thereby. This is partially supported by a polyp we found with an internal strobila comprised of seven early ephyra buds. The polyp is 10 mm in length, and the proximal and distal ephyra buds are generated at the positions of 3 mm and 8 mm, respectively. If only taking this body length as a criterion (>3 mm) for the competency of forming ephyra buds, 36% of the polyps (104 out of 292) from the debris dumps (Figure 1B) have the potential to release ephyras.

Deep-Sea Observation Technology. Macroplastics have been recorded in all types of deep-sea biodiversity hot spots, including submarine canyons, trenches, margin slopes, and seamounts by methods such as multicorer, box corer, bottom dredging, towed camera, ROV, or manned submersible.[10−17] Bottom dredging and underwater video are relatively inexpensive methods. Dredging could supply debris material for close examination, and video can offer distribution information in large deep-sea areas. In this study, the low occurrence frequency of macroplastics at dredging on continental shelves (200−300 km to the nearest shore) might be attributed to our observation strategy. To guarantee the safety of the research vessel, we only managed to dredge on random flat bottoms. Observations combining multibeam echo-sounder systems and ROVs[13,15] or a manned submersible (this study and others[11,16,18,19]) system might be the most efficient way in locating and collecting deep-sea macroplastic debris in further studies.

Conservation Implications and Practices. The role of deep-sea marine plastic debris as habitat for a variety of (sessile) organisms with its potential ecological effects has not been addressed by any international environmental organizations or projects, including the well-known United Nations Environment Programme.[3] We recommend adding the biota information, as presented in this work, to the routine monitoring of plastic debris in the deep-sea and initially giving high priority to hot spots such as deep-sea canyons, where debris is transported to and accumulated at the highest density.[12,13,15,43] We recommend that macroplastic items should be collected and gathered to eventually set up a regional or worldwide baseline database for colonized and associated organisms with DNA data. The integrative examination methodology and the preliminary data set contributed by this study (Table S1) are manageable and could be adopted for reference in the future.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.0c00967.

> Additional information for Materials and Methods in detail (Section S1), collecting localities (Figure S1), general appearance and chemical composition of investigated plastic items (Figures S2, S3), identification results of associated organisms adopting integrative approach (Section S2 and Figures S4−S6) (PDF)
>
> Tables for investigated plastic materials (Tables S1−S4) and relevant comparative (reviewed) materials (Tables S5−S7) (XLSX)

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Author Contributions

[§]X.S. and M.L. contributed equally to this work. X.S. conceived the study. X.S., C.K., and X.P. designed the research. X.S. and M.L. collected the bottom-dredging samples and prepared the first draft. X.P., X.Z., and K.T. collected the submersible samples and conducted the chemical identification of all plastic items. I.A. collected the Antarctic samples and hosted X.S. during his visit to KOPRI examining the Antarctic specimens. M.L., X.S., Y.W., and Y.G. conducted morphological and molecular analyses. M.L., G.P., and B.R. identified the egg capsules and prepared the literature review of gastropods. B.R., J.S., and J.H. conducted micro-CT examinations. X.L. prepared the artistic reconstruction. All authors wrote the paper.

Notes

The authors declare no competing financial interest.

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