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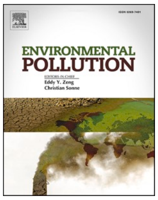

Journey to the deep: plastic pollution in the hadal of deep-sea trenches.☆

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ABSTRACT

The global increase of plastic production, linked with an overall plastic misuse and waste mismanagement, leads to an inevitable increase of plastic debris that ends up in our oceans. One of the major sinks of this pollution is the deep-sea floor, which is hypothesized to accumulate in its deepest points, the hadal trenches. Little is known about the magnitude of pollution in these trenches, given the remoteness of these environments, numerous factors influencing the input and sinking behavior of plastic debris from shallower environments. This study represents to the best of our knowledge the largest survey of (macro)plastic debris sampled at hadal depths, down to 9600 m. Industrial packaging and material assignable to fishing activities were the most common debris items in the Kuril Kamchatka trench, most likely deriving from long-distance transport by the Kuroshio extension current (KE) or from regional marine traffic and fishing activities. The chemical analysis by (Attenuated Total Reflection Fourier transform infrared (ATR-FTIR) spectroscopy revealed that the main polymers detected were polyethylene (PE), polypropylene (PP) and nylon. Plastic waste is reaching the depths of the trench, although some of the items were only partially broken down. This finding suggests that complete breakdown into secondary microplastics (MP) may not always occur at the sea surface or though the water column. Due to increased brittleness, plastic debris may break apart upon reaching the hadal trench floor where plastic degrading factors were thought to be, coming off. The KKT's remote location and high sedimentation rates make it a potential site for high levels of plastic pollution, potentially making it one of the world's most heavily contaminated marine areas and an oceanic plastic deposition zone.

1. Introduction

Plastic is indispensable for the modern lifestyle, the versatility of this material leads to its usage in innumerable sectors, with packaging, building and construction being the largest end-use markets (Europe, 2020). In 2020 the world's plastic production reached 367 Mt, almost 50% of it located in Asian countries, headed by China, the major plastic producer worldwide (Europe, 2020). Public awareness has increased during the last years, and global plastic legal framework and policies are working towards the regulation of plastic use and plastic waste (European Commission and Directorate-General for Environment, 2019). Nevertheless, the durability of plastic materials, combined with mismanagement of its usage during the past decades, leads to long term repercussions whose effects will be visible for undetermined time. The marine environment highlights the overall presence of plastic pollution on Earth as none of its realm is free from plastic (Everaert et al., 2020). The interconnection of the ocean by marine currents, combined with the transportability of buoyant plastic, makes plastic pollution a global issue. The buoyancy of plastic items is determined over time, as several processes such as weathering and biofouling (Koelmans et al., 2017) are proposed to cause quick loss of buoyancy, breakdown and sinking of plastic down to the seafloor (Kooi et al., 2017). Especially at abyssal and

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hadal depths, where the main degradation factors, such as photo-degradation and wave action are missing (Min et al., 2020), plastic accumulate and persists.

The ocean hadal (at depths greater than 6000 m) is represented by oceanic trenches (Hiraoka et al., 2020), the deepest representatives are located in the Pacific Ocean (Jamieson et al., 2010) and are considered one of the remotest and pristine environments in the marine realm (Jamieson et al., 2019). Recent records of plastic at the trenches floor, highlights the ubiquity of the human footprint even in places that are inaccessible for humans (Chiba et al., 2018). The northernmost west Pacific hadal trench, the Kuril Kamchatka trench (KKT), has been analyzed recently for microplastic (MP) pollution at its hadal (Abel et al., 2022), and abyssal depths for anthropogenic litter (Fischer et al., 2015). Both studies confirmed the presence of microplastic (<5000 μm) and microplastic (small MP; S-MP <500 μm and large MP; L-MP 500–5000 μm) and a heterogeneous distribution between sampling sites and throughout the sediment column (investigated in the upper 5 cm of sediment by analyzing sediment cores). Serious concern rises regarding this environment for being a hotspot of plastic accumulation, defining trenches as major depositories for MP/plastic pollution (Peng et al., 2020) (Shimanaga and Yanagi, 2016). The peculiar v-shaped morphology of hadal trenches, steep walls and the bathymetry of the hadal floor might favor plastic accumulation triggered by a funneling effect and seizure of plastic from the surrounding deep sea (Du et al., 2021). This assumption raised when relative high quantities of benthic biomass was measured in hadal trenches, higher than in adjacent abyssal plains (Danovaro et al., 2002). This was associated to peculiar sedimentation dynamics, related to the trench system and its geomorphology (Xu et al., 2018). In fact, the orientation and steepness of local slopes are the drivers of organic sediment funneling, suggesting that higher biomass can be found in accumulation areas such as the trench floor (Jamieson et al., 2010). Despite this assumption the hadal floor is largely unknown and quantification of marine litter scarce. This study investigates the presence of plastic debris at the hadal of the KKT. The samples were collected via Agassiz-trawl (AGT) and epibenthic-sledge (EBS) and are to our knowledge, the deepest trawls ever performed for plastic pollution research purposes. By evaluating the potential formal use of detected plastic debris and its polymer composition we aimed to (1) gain information of possible sources of plastic debris found in the hadal KKT (2) to investigate the link between macroplastic and MP pollution by confronting their polymer diversity and distribution at the hadal floor and finally to (3) gain information of the fate of plastic and MP in hadal trenches.

2. Material and methods

Samples were collected in summer 2016 during the German-Russian expedition Kurambio II, onboard RV *Sonne*. Thirteen stations (Fig. 1) were trawled with an Agassiz-Trawl (AGT; OKTOPUS GmBH, Kiel, Germany, 350 cm width, 70 cm height, net dimensions: 3.5 × 8.7 m and mesh size 10 mm), 10 stations were sampled with epibenthic-sledge (EBS; B-EBS, Brenke, 2005, stainless steel gear 360 cm length, 110 cm width, 180 cm height, equipped with supra- and epibenthic samples processing two sample nets: 500 μm on top and 300 μm at the cod ends). Sample ID, station area, coordinates and depth are listed in Table 1. In samples collected via AGT, the plastic component of Anthropogenic litter (size range >10,000 μm) were sorted out from the collected sediment onboard the research vessel and stored in Kautex bottles at 4 °C for further analysis. Sediment samples collected via EBS, were fixed with ethanol 96% and stored at 4 °C in Kautex bottles. Subsequently, the EBS samples underwent a visual sorting under a stereomicroscope (Olympus SZX16, Olympus, Germany), at 100–400 magnification. Putative plastic (size range >300 μm) were selected based on the following criteria: the lack of cellular structures, bright and even coloration and a solid texture (Rocher et al. 2021). Subsequently these particles were transferred into glass petri dishes, photographed and measured (length at their longest dimension and the orthogonal dimension at their brightest point) (Simon et al., 2018) under a microscope (Olympus DP26 Digital Camera,

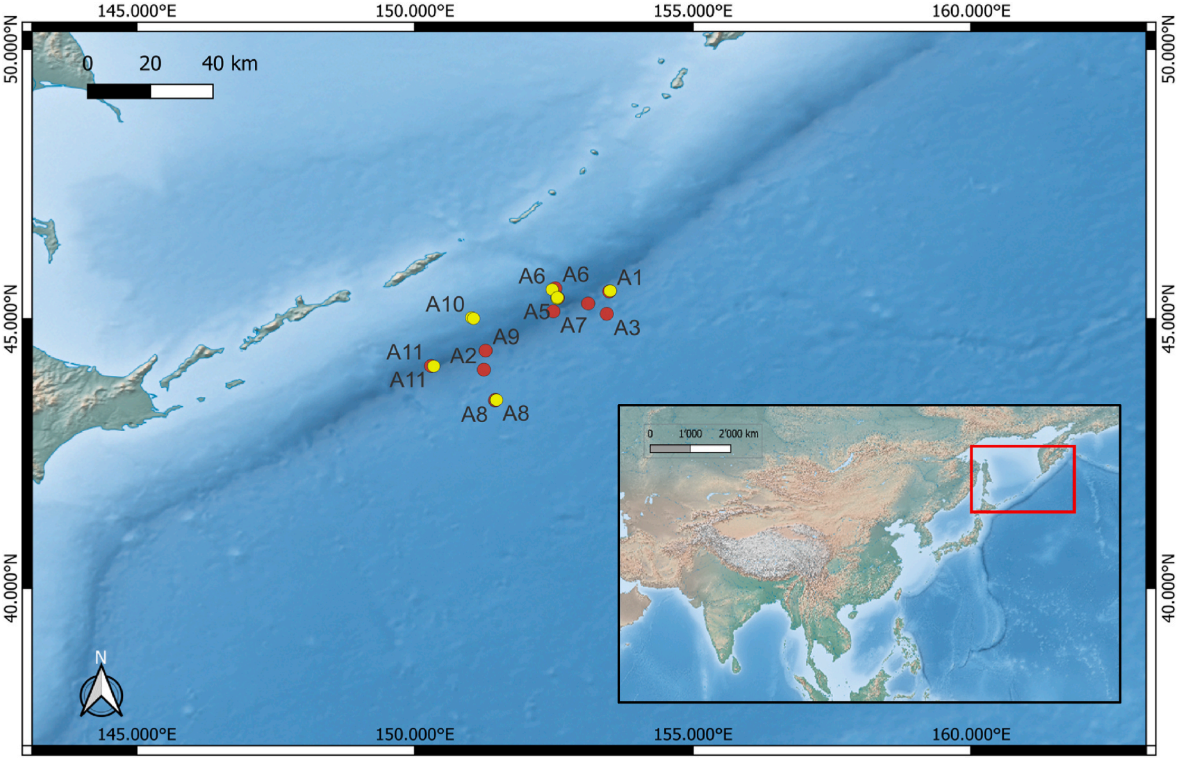

Fig. 1. Overview of the sampling area, sampling stations (labeled with area ID). Yellow dots on the map depict the location of the sampling area in the trench, sampled via epibenthic-sledge (EBS), red dots via Agassiz trawl (AGT). Double ID indicates that in that area, both trawls were performed. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1

List of trawls, specified by gear typology, trawl ID, area ID and depth. Lat_start N/l ong_start E and Lat_end N/long_end E defines the coordinates of beginning and end of a trawl. The distance trawled is reported in m and was calculated from the distance between the coordinates of start and end of the trawling. The surface trawled is reported in m^2 and the number of items detected reported in items/km^2. Grey rows depict abyssal depths, white rows, hadal depths.

sample ID (SO250)	mesh size (μm)	Station ID	Depth [m]	Distance [m]	Lat_start N/long_start E	Lat_end N/long_end E	m2 trawled	Items/km2
AGT9	10,000	A8	5134	1518	43° 49.81′ N 151° 44.78′ E	43° 48.07′ N 151° 48.07′ E	5313	94
AGT7	10,000	A8	5210	1440	43° 48.43′ N 151° 44.35′ E	43° 47.64′ N 151° 44.51′ E	5040	60
AGT64	10,000	A3	5739	1880	45° 50.86′ N 153° 49.56′ E	45° 09.99′ N 153° 46.62′ E	6580	106
AGT29	10,000	A6	6183	2180	45° 51.32′ N 153° 50.08′ E	45° 56.57′ N 152° 54.49′ E	7630	52
AGT98	10,000	A2	6446	2280	44° 05.53′ N 151° 24.25′ E	44° 06.25′ N 151° 25.93′ E	7980	25
AGT41	10,000	A5	7154	2219	45° 39.23′ N 152° 56.68′ E	45° 40.11′ N 152° 58.36′ E	7766.5	64
AGT43	10,000	A5	7241	2592	45° 38.51′ N 152° 56.77′ E	45° 38.51′ N 152° 58.37′ E	9072	121
AGT20	10,000	A1	8191	2571	45° 51.32′ N 153° 50.08′ E	45° 52.20′ N 153° 51.43′ E	8998.5	44
AGT18	10,000	A1	8200	1825	45° 50.86′ N 153° 49.56′ E	45° 51.95′ N 153° 51.25′ E	6387.5	219
AGT90	10,000	A9	8255	2398	44° 40.95′ N 151° 27.34′ E	44° 41.99′ N 151° 26.32′ E	8393	48
AGT54	10,000	A4	8729	1710	45° 28.50′ N 153° 11.53′ E	45° 28.12′ N 153° 10.10′ E	5985	100
AGT103	10,000	A11	9293	695	44° 12.49′ N 150° 29.42′ E	44° 12.50′ N 150° 37.25′ E	2432.5	699
AGT78	10,000	A7	9582	1272	45° 13.97′ N 152° 48.98′ E	45° 14.48′ N 152° 47.73′ E	4452	225
EBS10	500	A8	5120	1754	43° 49.43′ N 151° 46.96′ E	43° 48.45′ N 151° 47.17′ E	1929.4	52
EBS8	500	A8	5136	1597	43° 49.55′ N 151° 46.25′ E	43° 48.59′ N 151° 46.47′ E	1756.7	/
EBS85	500	A10	5265	1514	45° 02.26′ N 151° 02.14′ E	45° 01.64′ N 151° 03.68′ E	1665.4	/
EBS87	500	A10	5492	1398	45° 00.76′ N 151° 05.53′ E	45° 01.65′ N 151° 05.52′ E	1537.8	65
EBS28	500	A6	6051	315	45° 54.43′ N 152° 47.02′ E	45° 54.52′ N 152° 47.20′ E	346.5	289
EBS40	500	A5	7081	2691	45° 38.00′ N 152° 55.95′ E	45° 40.83′ N 152° 57.68′ E	2960.1	338
EBS42	500	A5	7123	2102	45° 39.62′ N 152° 56.39′ E	45° 40.26′ N 152° 57.63′ E	2312.2	43
EBS17	500	A1	8191	1645	45° 52.04′ N 153° 51.39′ E	45° 51.40′ N 153° 50.41′ E	1809.5	55
EBS19	500	A1	8196	1659	45° 52.02′ N 153° 51.15′ E	45° 51.41′ N 153° 50.21′ E	1824.9	55
EBS102	500	A11	9545	1626	44° 11.99′ N 150° 34.07′ E	44° 12.00′ N 150° 32.74′ E	1788.6	168

Olympus) using image analysis software (cellSens, Olympus). All items and particles collected with both devices, were identified individually, categorized by their shape following the OSPAR guidelines for anthropogenic litter (Wenneker and Oosterbaan, 2010) and chemically identified using an Attenuated Total Reflection Fourier transform infrared (ATR-FTIR) spectrometer (Bruker Tensor 27 coupled to diamond platinum ATR unit, Bruker Optik GmbH, Germany). The IR spectra were recorded over a wavenumber range of 400–4000 cm^{-1} and compared against a reference FTIR library of plastic particles sourced from the environment databases of Primpke et al. (2020) Roscher et al. (2021) and (FLOPP-e) (De Frond et al., 2021) implemented with the IR spectra of the SONNE vessel lack coating, using the SiMPle software (Primpke et al., 2020). Particles with a match of at least 0.7 (out of 1) were counted as safely identified. Spectra with a match between 0.6 and 0.7 were categorized as "unsafe" and were accepted or rejected by revaluating the presence of prominent bands with the best library matches, manually (Rocher et al., 2021). Particles with a match below 0.6 were discarded and considered as not spectroscopically identified. To allow a comparison with the plastic debris load found in other studies conducted in the deep Pacific Ocean seafloor (Ioakeimidis et al., 2015), the number of debris and particles detected, were extrapolated to Items/km^2, by considering the surface area sampled and the number of debris found for every trawl.

2.1. *Statistical analyses*

Pearson correlation was calculated to evaluate possible correlations between the abundance of plastic items and trawl depth, distance from the adjacent island arc and along the trench axis (to visualize if plastic pollution increases with decreasing distance from the Kuroshio current), respectively (R development Core Team, version 4.1.2).

3. Results

Anthropogenic litter was found in all the 13 AGT samples, with a total of 92 items from a depth between 5134 and 9582 m. Eleven different classification categories were determined: tangled net, cord rope strings, string and cord Ø < 1 cm, strapping band, fragment, sealing ring, plastic fragment, plastic sheeting, paint chip packaging, industrial packaging, can (lid) (see Fig. 2a and b). Most debris were categorized as string and cord Ø<1 cm (33%) followed by plastic fragment (23%) and industrial packaging (11%). On six plastic debris, clear labels were distinguishable, and written in Japanese (two items), Korean (three items) and Spanish (one item) languages (Fig. 2a).

Anthropogenic litter found in the Kuril Kamchatka trench: tangled nets, cord, rope and strings, packaging and aluminium.

Macroplastic found in the Kuril Kamchatka trench: plastic sheeting, stripping band and plastic fragments.

Concerning the chemical identification, a total ten different polymer types were detected, Polypropylene (PP) was the most represented, accounting for 30% of the total polymer composition, followed by High-density polyethylene (HDPE; 19.5%), Low-density polyethylene (LDPE; 17%) and Polyethylene (PE; 13%). Nylon and Polyamide-fiber (PA-Fiber) accounted for 6.5% and 4% respectively. The remaining debris were identified as Polyethylene chlorinated (PE-CL), Polyester (PEST), Polystyrene (PS) and aluminum (ALU; 2.6% for each type) (to visualize the spectra, consult SI, Fig. SI1).

Debris with a spectral match below 0.6 (22% of the total debris collected) were considered as not chemically identified, yet these items were clearly of anthropogenic origin (as visible in Fig. SI2, in the supplementary information), and were thus classified as anthropogenic litter.

Anthropogenic litter was found in eight out of 10 EBS, with exception of EBS8 and EBS85 (area A8 and A10 respectively). From 47 putative anthropogenic particles, collected from 10 trawls from 5120 to 9545 m depth, a total of 26 could not be chemically identified as the spectral matches never exceeded 0.5, and were excluded from the survey. The majority of the particles were plastic fragments (80%), fiber-like plastic and plastic foil were equally represented and accounted for the remaining 20%. The chemical identification revealed that two fibers were from natural origin, and therefore excluded from the total plastic count, the remaining particles were identified to be made of as the following six polymer types: LDPE, accounting for 16%, PE and Polymethacrylate (PMMA) for 10% PP and PE for 5% (see Fig. SI1). Fifty-two percent of the particles were clearly of anthropogenic origin (see Fig. SI2), but could not be identified chemically via ATR-FTIR.

Overall the debris load was of 106 items/km^2, with two out of 23 trawls not containing debris at all and a maximum number of 699 items/km^2 in AGT 103, dragged at 9293 m depth. Trawls from the abyssal of the trench (<6000 m) were those with a relative low items load, in fact

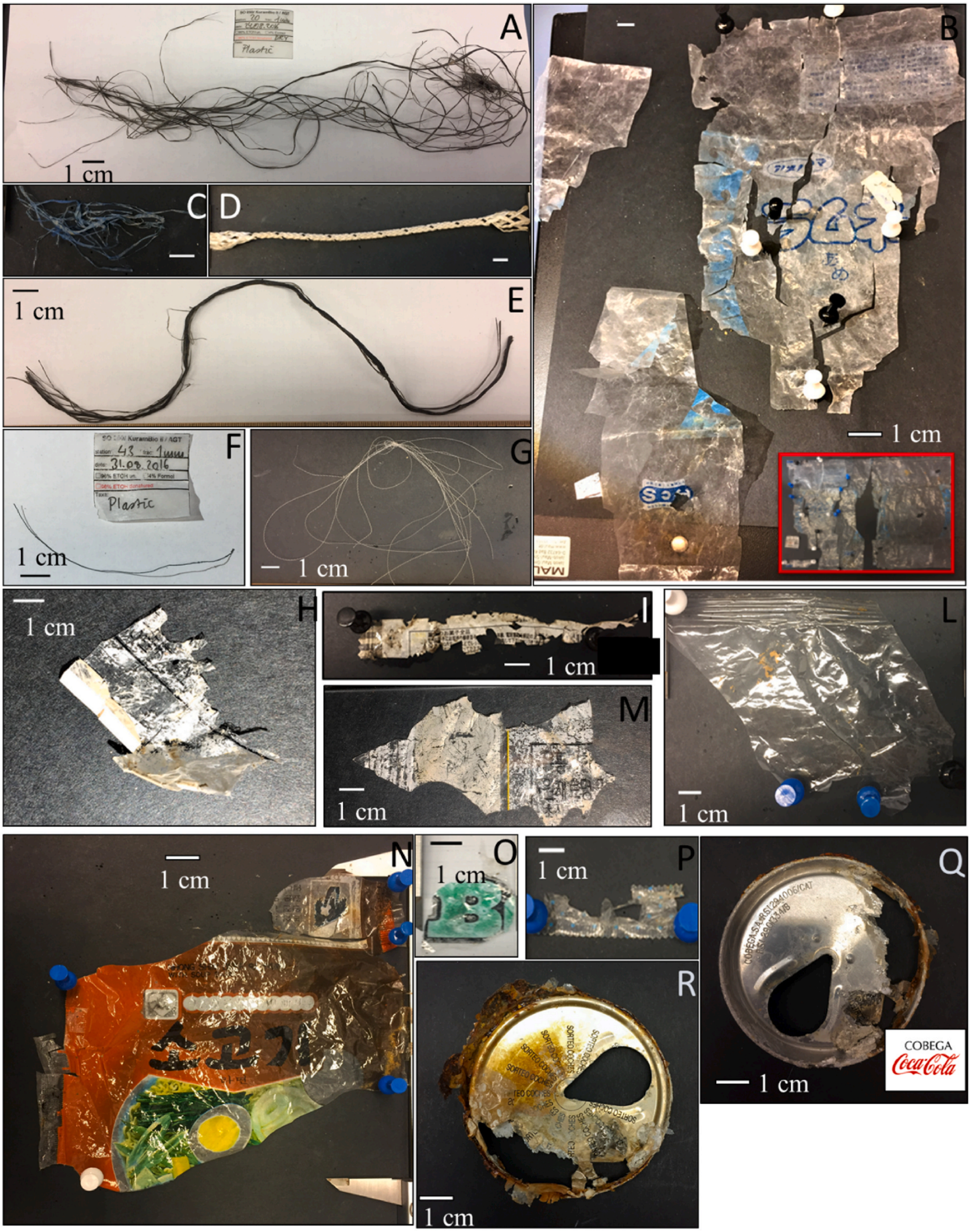

Fig. 2a. Anthropogenic litter found in the trench: debris A, C, D, E, F and G were categorized as tangled nets, cord, rope and strings; B, and H to P as packaging and Q and R (both sites are depicted to highlight the labels) as can lid. The packaging in figure B was rebuilt from fragments found in the trawl and displayed in its entirety in the red square. The flags in figure B, H, I, M, N and R depict the language of the labels. The code of the can lid in picture Q reveals the producing company of the beverage which was contained in the can. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the two trawls which didn't contain any plastic (EBS8 and EBS85) were performed between 5120 and 5136 m respectively and remaining 5 trawls at this depth did not exceed a plastic number of 106 items/km^2. Statistical analysis didn't reveal any correlation of items load and depth (see SI), nonetheless the highest values were found at hadal depths: EBS28 (6051 m) with 289 items/Km^2, EBS40 (7081 m) with 338 items/km^2, AGT18 (8200 m) with 219 items/km^2, AGT103 (9293 m) with 699 items/km^2, and AGT78 (9582 m) with 285 items/km^2.

A detailed mapping of trawled locations and anthropogenic litter found and polymer composition is displayed in Fig. 3 the extrapolation to items/km^2 for every trawl, both AGT and EBS, is reported in Tab. SI 1.

The statistical analysis did not reveal any correlation between the

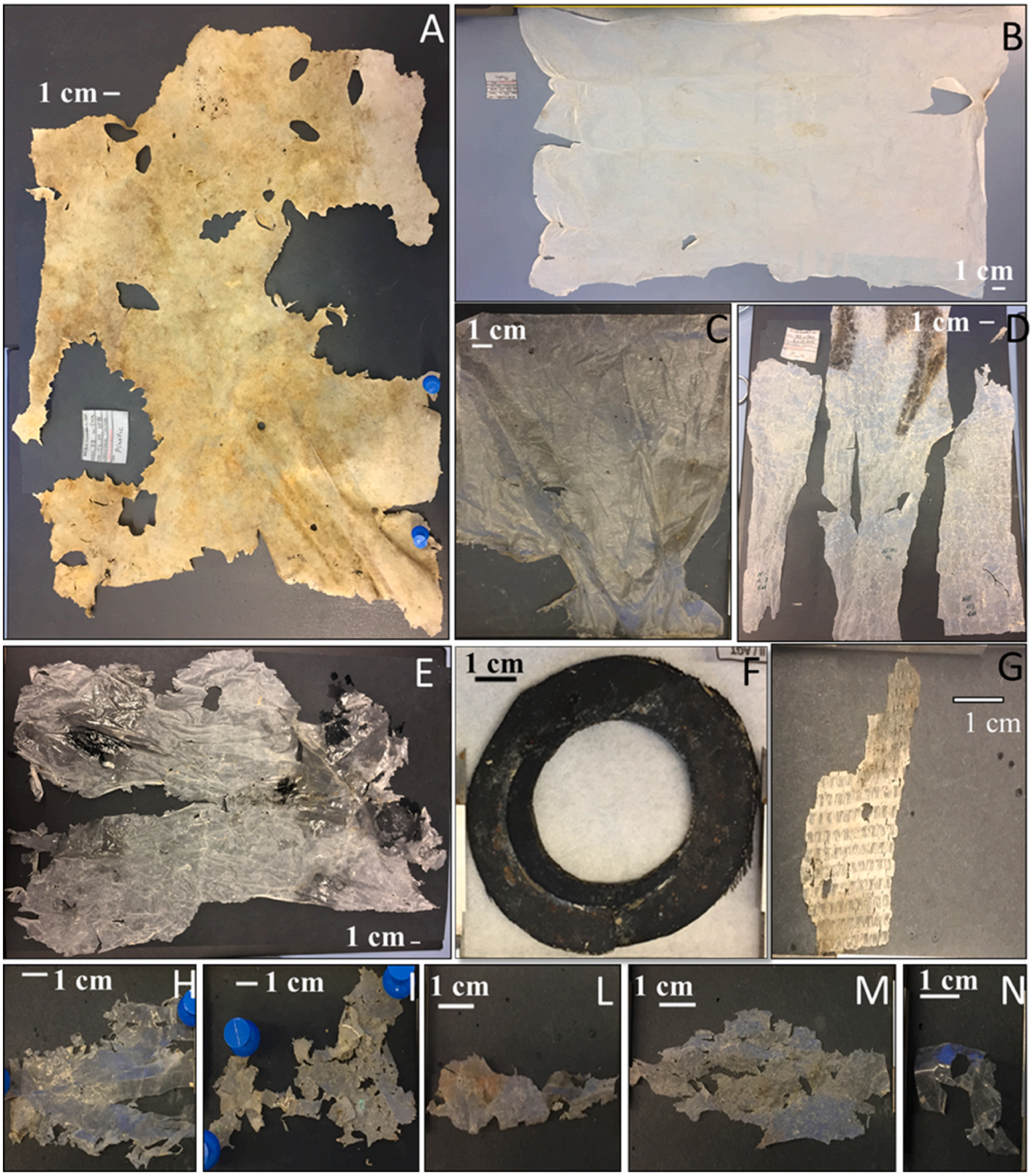

Fig. 2b. debris A to E were categorized as plastic sheeting, F as sealing ring G as fragment of a stripping band and H to N as plastic fragments.

abundance of anthropogenic litter and trawl depth nor with relative location/distance to the island arc and distance to the KE (Se SI).

3.1. *Detected anthropogenic litter per sample*

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4. Discussion

The presence of plastic debris at hadal depths is undeniable since footage showing a plastic bag at the Challenger deep in the Marianna trench was disclosed (Chiba et al., 2018). However, since then, information of an adequate number of items characterized both by shape/-usage purpose and chemical composition, was fundamentally missing. Here we provide information on chemical composition, shape and, whenever possible, former use of 111 items collected at depths ranging between 5134 and 9582 m form the hadal KKT floor. This dataset allows corroboration of several assumptions, that were previously forebode based on significantly lower survey numbers (Peng et al., 2020) or investigations among hadal trenches at comparable depths (Chiba et al., 2018).

4.1. *Sources*

The majority of items detected, based on their appearance and polymer composition, were identified as fishing line and ropes, followed by packaging material or fragments resulting from its deterioration. In line with observations of floating litter in the Pacific Ocean (Lebreton et al., 2018), the reasons why these very two categories are predominant is consequent, among other factors described further, to the global

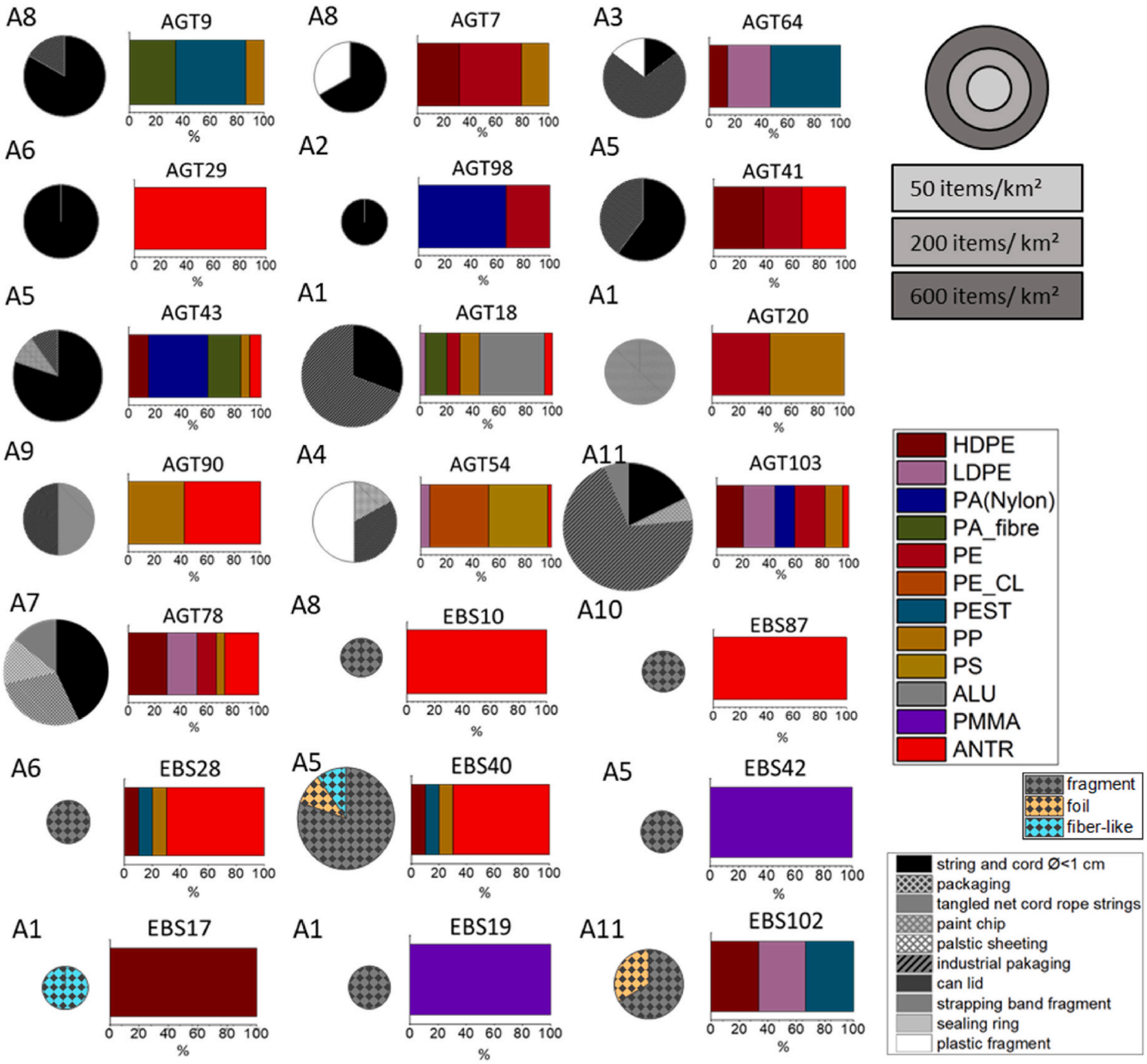

Fig. 3. Detected anthropogenic litter per sample. The scaled pie charts refer to the abundance and typology of anthropogenic litter (reported as items/km2, the bar charts refer to the relative polymer composition). HDPE: high density polyethylene, LDPE: low density polyethylene, PE polyethylene, PE-CL: polyethylene chlorinated, PP: polypropylene, PS: polystyrene, PA: polyamide, PEST: polyester/polyethylene terephthalate, ALU: aluminum, PMMA: Polymethacrylate, ANTR: anthropogenic origin.

plastic production and to the location of the trench. In fact, the first reason may explain the predominance of packaging material and single-use plastic items in the trench as this is one of the largest uses of plastic on global scale (Geyer et al., 2017). The location explains the high quantities of lines, cords and ropes as the Kuril Islands adjacent to the trench, are intensely exploited as naval trade routes, and fishery (Abel et al., 2021). Compared to other sources of plastics, those that predominate, whether on a global or local scale, are likely to contribute a greater proportion to the total plastic load (Boucher and Billard, 2019). However, as deducible from countless studies conducted (Van Sebille et al., 2020) on the transport and fate of both marine debris and MP in the marine realm, local sources aren't the only. Specifically, for the NW Pacific Ocean, plastic pollution is connected to substantial plastic sources in Asia and are transported through the Kuroshio Extension (KE) current system (Lebreton et al., 2018). This observation is supported also by a considerable accumulation of benthic plastic debris at the abyssal seafloor beneath this current (Nakajima et al., 2021). Micro- and mesoplastics are also transported northeastward from the Sea of Japan by the Tsushima Current via the Tsugaru and Soya straits in the NW Pacific Ocean (Iwasaki et al., 2017), providing an alternative route for plastic to reach the region. Evidence of this transport might be that on several sweets, instant food and rice packages found in the KKT, labels in Korean, Chinese and Japanese, were still distinguishable (Fig. 2a). Nonetheless, this evidence might also be an artefact of globalization and the resulting export of these products to other countries. In support of this statement was the recovery of a can lid with Spanish labels, at 8200 m depth, belonging to one the world's famous soda exporting company. It is important to consider that generally, to model the provenience and the path of marine debris, GPS loggers on floating devices, numerical modeling's and remote sensing are the most effective approaches to track and determine the pathway of marine debris (Van Sebille et al., 2020). However, it also needs to be considered that the inaccessible depths of the trench and its fair distance from the sea surface let such a research effort and its accuracy to be of little use, given the innumerous oceanographic and biologic events affecting the sinking behavior of particles trough the water column, down to hadal depths (Van Sebille et al., 2020).

4.2. Links between macroplastic and microplastic

Despite the obvious link between macro- and microplastic pollution in the ocean (Martínez et al., 2020) the quantification and characterization of these in the environment are mostly not objectives of a common approach. This is not surprising as the set-up for their investigation differs significantly, starting from the sampling, sample processing, particle identification and ending with data representation and interpretation (Gomiero et al., 2018). Nevertheless as, especially in the marine realm, the breakdown of larger plastic debris into MP is largely discussed (Jahnke et al., 2017), the attention should be draw on the contribution of larger plastic litter to the ocean MP budgets. A common evidence in literature is that the abundances of plastic particles increase with decreasing particle size (Abel et al., 2021) supporting the idea that debris floating in the ocean, exposed to weathering effects, break down into smaller and smaller fragments and becomes increasingly preponderant in the ocean MP budget (ter Halle et al., 2016). The deep-sea is considered an especially important depocenter for those plastic debris and MP that are not retained by the rivers or are not stranded after entering the ocean (Weiss et al., 2021). Moreover, the absence of the main weathering effects such as UV light and wave action, and a consequent less effective degradation processes (Van Sebille et al., 2020) has led to the assumption that, once plastic debris enters the trench system, they perpetuate and the degradation process slows down considerably. In this light, the stability of a polymer which is based on their molecular structure, and the sinking behaviors of particles influenced by their size, shape and their interaction with biotic and abiotic events (Van Sebille et al., 2020), can strongly influence the nature of pollution at the hadal floor. In this study PE (41%) and PP 20.5%) were the most represented polymer types of foils and packaging items (Fig. 4b). Considering their molecular structure, the catalyst residues of PE and PP make these two polymer types being susceptible to photodegradation (Van Sebille et al., 2020), but at the same time the lack of functional group make them less prone to enzymatic and abiotic hydrolysis degradation (Min et al., 2020). Therefore, these two polymers are more likely to degrade at the sea surface. Thus, debris made of these polymers may reach the hadal floor without suffering particular degradation/weathering and consequent break down except for degradation occurring in the ocean surface. Moreover, packaging tends to be enriched with additives and dyed due to guarantee properties such as elasticity of the packaging, to enhance the attractivity or to advertise a product (Min et al., 2020). This chemical may prevent the degradation of these plastics even after it has served its purpose (Ambrogi et al., 2017). PE and PP in the trench are represent not only in form of microplastic, those were also preponderant polymers in the MP fraction, suggesting the presence of both pollution types, macroplastic and MP, at the hadal floor (Abel et al., 2022) (Fig. 4a). The similarity of the polymer composition between marine debris and MP is, anyway, not to be taken for granted and depends on the type of polymer considered. Studies (Abel et al., 2021; 2022) reported the presence of MP in the deep sediment of the KKT, and this was spectroscopically characterized in its chemical composition revealing 14 to 15 different polymer types. Accordingly, to these findings, MP was mostly identified as Acrylates/(Polyurethane) PUR/varnish PE and PP and a minor proportion by, ethylene vinyl acetate (EVA), polyamide (PA), polycarbonate (PC), polyvinyl chloride (PVC) and polyester/polyethylene terephthalate (PEST). Nitrile rubber (NR) and rubber types (RT1 and RT3) were found in traces (Fig. 4a). The major polymer representants (PE and PP), as mentioned before were also found in this study, but no acrylates were found. Moreover, the less common polymer types in the S-MP size range are completely missing in L-MP and macroplastic. Interestingly, the polymer diversity of the plastic fraction >500 μm is not as high as the polymer diversity of S-MP, being represented by 10 polymer types, four of this representing less than 20% of the total polymer composition. Premising that assumptions of MP investigations from environmental samples as well as differences in the analytical approach are always to be treated with a certain degree of uncertainty (Abel et al., 2022); a mismatch in the polymeric composition between items recovered in this study and that of MP found in Abel et al. (2021, 2022), is indisputable (Fig. 4). Of particular note is the absence of PUR and varnish and

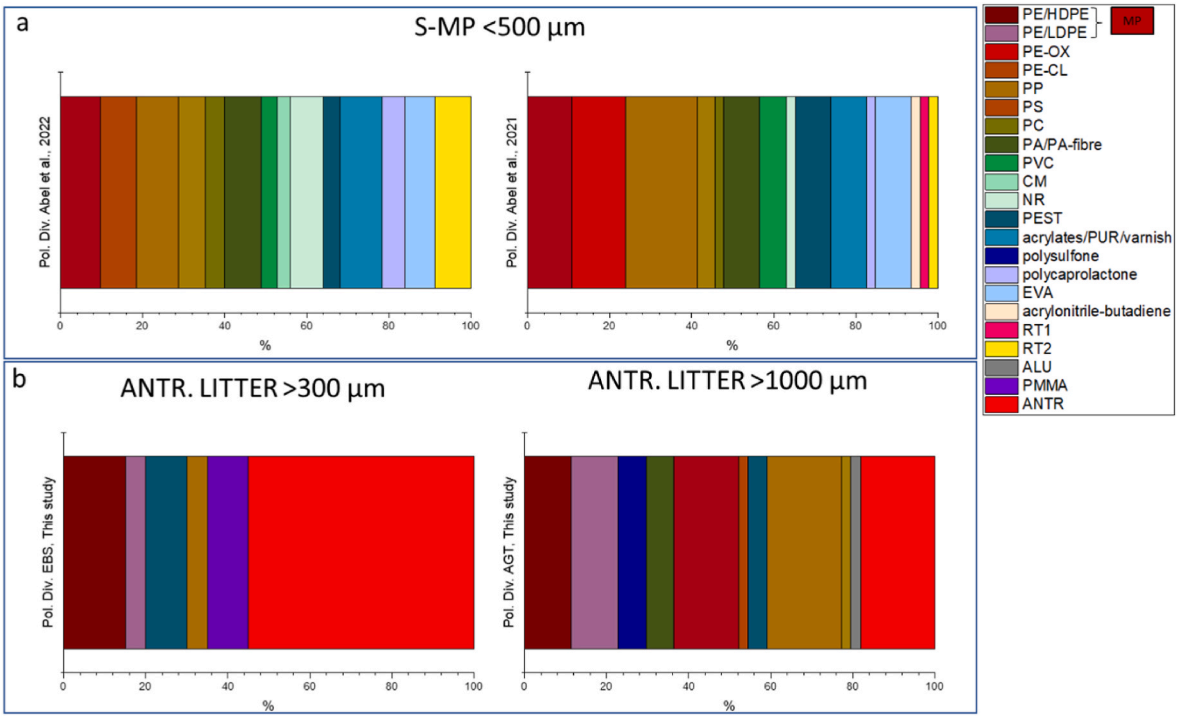

Fig. 4. Polymer composition of small microplastic (S-MP) (Abel et al., 2021, 2022) and anthropogenic litter (ANTR. LITTER) (this study) detected in the Kuril Kamchatka trench. PE: polyethylene, HDPE: high density polyethylene, LDPE: low density polyethylene, PE-OX polyethylene oxidized, PE-CL: polyethylene chlorinated, PP: polypropylene, PS: polystyrene, PC: polycarbonate, PA: polyamide, PVC: polyvinyl chloride, CM: chemically modified cellulose, NR: nitrile rubber, PEST: polyester/polyethylene terephthalate, PUR: polyurethane, EVA: ethylene vinyl acetate, RT1: rubber type one, RT2: rubber type two, ALU: aluminum, PMMA: Polymethacrylate, ANTR: anthropogenic origin.

acrylates, which predominate in the MP fraction. A possible explanation for these missing polymers in the bigger size fraction is that PUR, acrylates and varnish MP may derive from paints and coatings also used for ships and other marine structures (Leistenschneider et al., 2021) that are particularly brittle (Song et al., 2015) and tend to break down easily under marine environmental conditions. This and the absence of varnish, acrylates and PUR debris in EBS and AGT samples may suggest that plastic items with a certain polymeric composition (e.g. Acrylates, PA and PS) are subject to weathering processes in the upper layers of the ocean and reaches the hadal already as MP. This is also supported by the fact that in the trench sediment the number of μAcrylate particles increased by decreasing particle size, especially in particles smaller than <50 μm. Also, the other polymer types such as PS and PA can break down into smaller pieces, and reach the trench as secondary MP. Based on this, the sources of plastic pollution in the trench, both MP and macro debris are, to be considered free-standing and MP reaches the trench as such from the ocean surface. In fact, polymers found in the micron range were missing in the bigger fraction, and the polymer diversity increased with decreasing size. However, a certain degree of degradation of sedimented debris can take place also at the hadal floor, suggesting the formation of MP also in the trench itself. Some objects, in fact, showed marked degree of brittleness to such an extent, that the entire object had been reconstructed from its pieces (see Fig. 2a debris B). This finding suggests that plastic debris that ends up in the trench, are already weathered and for this they can degrade also in locations where degradation factors are relatively weak and/or other factors, such as chemo degradation or piezophiles microbial degradation, replace missing degradation factors such as UV light (Sekiguchi et al., 2010). As all the pieces of the same debris were found close to each other at the trench ground, at least in the same trawling event, the object likely broke down *in loco*, otherwise the fragment would had been get spread in the water column (e.g. by currents and vortices (Abel et al., 2022)) while reaching the ground (Kane et al., 2020) and the fragments would have settled in different locations. This, contextualized once again to the link existing between marine litter and MP pollution, can be a concourse of heterogeneous distribution of MP distribution at the trench floor (Filgueiras et al., 2019). If a plastic fragment degrades at the trench floor, this point will consequently have a higher MP abundance than elsewhere. Finally, if circumstances related to the sedimentary environment and biotic activities such as particle burial and bioturbation (Näkki et al., 2017) can redistribute particles along the sediment column (Abel et al., 2022), and perpetuate in that location without being affected from recasting events.

4.3. Comparison with plastic debris levels in areas adjacent to the trench

Studies revealing plastic pollution in the deep sea (Peng et al., 2020) (Abel et al., 2021) (Jamieson et al., 2019) (Nakajima et al., 2021) are, compared to other environments, scarce. Combining the relatively low number of studies with the fact that the deep-sea covers nearly two-thirds of Earth's surface (Woodward, 2003), makes it clear how largely unknown the extent of plastic pollution at the marine sea floor is. To add uncertainties is the heterogeneity of this realm (Zeppilli et al., 2016), different sources of contamination (Almroth and Eggert, 2020) and the great number of factors acting on sinking particles (Van Sebille et al., 2020). It is therefore difficult to have representative and/or comparable data to assess the level of pollution of the deep-sea floor. In addition, marine litter abundances comparisons among non-harmonized sampling protocols, like in the majority of research fields, are carefully to be assessed given the high risk of misinterpretation (Schmid et al., 2021). Specifically, deep sea pollution surveys commonly make use of Autonomous and Remotely-operated Vehicles (ARV) (Chiba et al., 2018), human occupied vehicles (HOV) and video footage (Nakajima et al., 2021). This permits the visualization of debris *in loco* and the sampling of debris for further chemical identification if equipped with robotic arms. Trawling's as Agassiz trawl (AGT) and epibenthic sledge (EBS) used for zoological research, were also adopted as opportunistic methods for sample collection intended for marine litter identification studies (Fischer et al., 2015). These sampling methods allow to calculate the volume trawled by the gear size, and to detect also potential buried debris, not visible by the only surface screening (Ioakeimidis et al., 2015). However, this method, that can be defined as an opportunistic sampling method (Willis et al., 2017), allows to sample MP and plastic debris with a size range that depends on the mesh size of the sampling device used. In fact the mesh sizes in this study (300 μm and 10,000 μm) are common for zoological research purposes and does not match the canonical size classes in (M)plastic studies, usually defining small (S)-MP as particles smaller than 500 μm and large (L)-MP particles with a size range of 500–5000 μm (Rocher et al., 2021; Abel et al., 2022). The above described methods may all have strength and weaknesses. Specifically, for the selective sampling methods, buried and unseen items may not be detected, leading to an underestimation of the effective abundances (Ioakeimidis et al., 2015), while for the trawling it's the lack of a clear footage, what would elucidate the location of the collected items at the seafloor. However, it is important to keep in mind the challenging depths where these surveys are made and the uniqueness of the available data. For this, after due consideration and without going into too much detail in order to avoid misinterpretations and make unfounded assumptions, comparing the abundances of anthropogenic litter detected in the KKT with those of the adjacent abyssal plain revealed a considerably lower number of items. A previous study on Anthropogenic litter in the adjacent abyssal plain (Fischer et al., 2015) of the trench, revealed up to 2020 particles/m^2. This value has to be taken conscious of the uncertainties deriving from the extrapolations to 1 m^2 from an actual sampled volume of 0.25 m^2 (Fischer et al., 2015; Abel et al., 2021), different method applied to collect the sample (box corer against trawl) and different units used to quantify the particles. Nevertheless, the values are unequivocally higher in the adjacent abyssal plain than in the trench's hadal. In order to not mistakenly misinterpret these discrepancies in plastic abundances between abyssal plain and hadal trenches, that could be an artefact of different sampling approaches and data interpretation, we compared our findings with those of a similar selective sampling method, comparable investigated surfaces and the same unit reported (Nakajima et al., 2021). Also, the area fits with our purposes as in this study Nakajiama et al. (2021) investigated the presence of anthropogenic litter at abyssal depths beneath the Kuroshio extension, southwards of the KKT. Also, in this case abundance in the trench is 100 times lower than the adjacent abyssal plain.

Likely, the location of a trench, its trench system and the surrounding environment are the main drivers of plastic pollution at the sea floor, and also in trenches. The majority of plastic abundance records for trenches, targets MP and therefore a comparison is inappropriate due to different sampling procedures, particle extraction and quantification methods, (Peng et al., 2020). Differently, in the Ryukyu trench (ranging from 1.2×10^3 to 7.1×10^3 items/km^2) (Shimanaga and Yanagi, 2016) the plastic size target and the sampling method are similar to those exploited in this study: even though the sampling occurred mostly in the abyssal depth, abundances exceeds the values of debris in the KKT by one order of magnitude. This may be due to the specific location of the trench, as for example the Ryukyu trench is located south of the KKT, beneath the KE current, one of the main Plastic source and transport pathway of the NW Pacific Ocean (Lebreton et al., 2018).

5. Conclusions

This study is the first investigation of marine litter quantification, combined with spectroscopic characterization of polymer based on a reliable number of trawls, particle number and measurements at hadal depths. At comparable depths, in fact, only observations on litter were carried out, highlighting the presence of plastic, without quantifying it. By characterizing anthropogenic litter by its usage purpose, it was possible to distinguish the two main sources of plastic that settles at the trench floor, namely packaging and fishery, and by spectroscopic analysis, to identify the main polymer types, namely PE PP and Nylon. These polymers are relatively stable in the marine realm as they do not particularly suffer hydrolytic degradation and most likely end up at hadal depths without breaking down into smaller pieces. Nevertheless, already damaged polymers can incur in fragmentation also at the trench floor, down to secondary MP, thus contributing to the heterogeneous distribution of MP at the seafloor. By comparing the polymer composition of anthropogenic litter and MP in the KKT, it was noticed that the polymer diversity decreases with increasing size of the particles/items, and particularly brittle polymers such as varnish are only present as MP, suggesting that the sources of Plastic debris and MP are different. Finally, by comparing the plastic abundance found in the trench with those recorded in adjacent abyssal plains and with those of other Pacific Ocean located trenches, we are broadening the view that is missing in the statement “trenches are the trash bins of the ocean” and draw attention to the location of a trench, as an important factor to consider when plastic pollution is investigated. Nevertheless, assumptions like the forecasting fate of trenches to be the most polluted marine areas worldwide and oceanic plastic depocenters highlights the urgency of new policies for waste treatment and plastic production.

Authorship contribution statement

Serena M. Abel: Writing – original draft, Writing – review & editing, Visualization, Formal analysis, Methodology, Investigation. Sebastian Primpke: Software, – review & editing. Fangzhu Wu: Investigation, Writing – review & editing. Angelika Brandt: Project administration, Writing – review & editing. Gunnar Gerdts: Supervision, Formal analysis, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2023.122078.

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