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Marine litter in the deepest site of the Mediterranean Sea

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ABSTRACT

From the scientific viewpoint, the deepest ocean includes the least known regions on Earth. Advanced technologies, complex logistics and very specific expertise, requiring adequate funding, are needed for in situ observation of the deep sea. In this paper we present the results of the inspection of the floor of the deepest site in the Mediterranean Sea, the 5122 m in depth Calypso Deep in the Ionian Sea, with the Human Occupied Vehicle (HOV) Limiting Factor by Caladan Oceanic in 2020. The dive videos show the floor of the Calypso Deep littered by anthropogenic debris, with litter concentrations among the highest ever recorded in a deep sea environment. The dominant litter category by material type is plastics, accounting for 88 % of the identified litter items. No interactions have been found between litter and the rare life forms identified so far in the deep Ionian Sea. This illustrates that the deep sea is often a final sink for pollution and as such deserves more attention on associated processes and impacts. Harmonized monitoring and assessment should include the deep sea areas in order to enable efficient mitigation. Our findings provide a strong argument in favour of the urgent implementation at global scale of policy actions to reduce ocean littering thus easing the conservation of unique marine habitats, including the deepest on Earth. Our results also appeal to the society at large in terms of consumption habits, waste reduction, care of the environment and the pressing need for action to protect our ocean.

1. Introduction

Marine litter is an issue of global concern, and efforts to assess, identify, quantify and understand its sources, pathways, accumulation sites and impacts are crucial to raise awareness and plan mitigation strategies with associated measures (European Commission, 2008, 2018; UNEP, 2009; Werner et al., 2016; Löhr et al., 2017; Carlini and Kleine, 2018; European Union, 2019; Galgani et al., 2019, 2024; Mæland and Staupe-Delgado, 2020; Mediterranean Action Plan, 2021; UNEP/MED, 2021; UNEP, 2024).

Awareness about marine litter pollution, specially plastic, has increased drastically in the last decade (Eriksen et al., 2014; Löhr et al., 2017; Hartley et al., 2018; Haward, 2018; Abalansa et al., 2020; Thompson and De Falco, 2020; Bellou et al., 2021; Martins et al., 2021; UNEP, 2021), largely driven by observation of beach and sea surface littering that can be easily and directly spotted by citizens and scholars, as well as well-documented on impact on marine organisms (e.g. ingestion and entanglement). Scientific research altogether with the media have contributed significantly to awareness rising, including high impact findings such as, for instance, the harm litter may cause to

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marine organisms and habitats (Laist, 1997; De Stephanis et al., 2013; Kühn et al., 2015; Rochman et al., 2016; Angiolillo and Fortibuoni, 2020; Canals et al., 2021, and references therein), the discovery of plastic-made rocks on beaches (Corcoran et al., 2014; De-la Torre et al., 2021; Santos et al., 2022), or the giant garbage patches in major ocean gyres (Van Sebille et al., 2012, 2015; Lebreton et al., 2018; Lebreton, 2022).

Therefore, while coastal and sea surface littering is a very visible indicator of the marine litter problem —and, more generally, of the overall degradation of the ocean—, it is much less apparent in other marine compartments that are out of sight. This is, in particular, the case of the (deep) benthic compartment, even though the first evidence of litter on the seafloor dates back to 1975 (Holmström, 1975). Growing evidence —largely provided by imagery obtained with underwater vehicles— during the last three decades has shown the ability of marine litter, and especially of plastics of various sizes, to reach and accumulate on the seabed including the very deep seabed (i.e. deeper than 2000 m) Woodall et al. (2014). Some devoted databases are nowadays collecting both recent and early in situ imagery showing litter items on the bottom of our oceans and seas (e.g. Bergmann et al., 2017; Chiba et al., 2018). It should be kept in mind that litter items in early photographs and videos were largely neglected at the time, as marine littering was not yet perceived as a so big issue as it is today. Today, we know, for instance, that extensive litter dumps in some places —often referred to as "litter hotspots"— cover entirely, or almost, the seafloor (Galgani et al., 1996; Peng et al., 2019; Pierdomenico et al., 2019; Canals et al., 2021).

Marine litter is sourced either from land, mainly through river systems and artificial waterways, direct dumping along the seashore and by atmospheric transport of the lightest fractions (Galgani et al., 2015; Lebreton et al., 2017; Crosti et al., 2018; Prevenios et al., 2018; Chenillat et al., 2021; Ryan and Perold, 2021; Weiss et al., 2021), or directly at sea mostly from fishing activities and vessel discharges (Horsman, 1982; OSPA Commission, 2020; Deville et al., 2023). Once at sea, litter is subject to beach stranding, transport and redistribution by currents, degradation processes and vertical transport to the ocean's interior and the seafloor (Woodall et al., 2014; Gewert et al., 2015; Ourmieres et al., 2018; Declerck et al., 2019; De Haan et al., 2019; Hanke et al., 2019; Chamas et al., 2020; Maclean et al., 2021; Martin et al., 2022).

In order to efficiently assess the different sources and the current status, as well as to guide potential mitigation, removal and restoration initiatives, quantitative information of the whereabouts of marine litter in the different ocean compartments is required, including the least known ones, which are the vast expanses of the deep continental margins and basins (Ramirez-Llodra et al., 2010). As shown in previous studies, it is assumed here that a fraction of floating marine litter will ultimately sink, even if made of buoyant material, due to processes increasing its density, such as the loss of the lighter components and biofouling, ballasting, particle scavenging and, possibly, degradation (Thompson et al., 2004; Ioakeimidis et al., 2014, 2017; Kaiser et al., 2017; De Haan et al., 2019; Madricardo et al., 2020; Int-Veen et al., 2021). Litter in the water column is transported by ocean currents while sinking, with the deposition on the seafloor being a function of the sinking velocity and the current strength (Galgani et al., 1996; Gabitto and Tsouris, 2008; Schlining et al., 2013; Madricardo et al., 2020). Obviously, dense marine litter, mainly from sea-based sources but also from land-based sources, accumulates directly on the seafloor. There are known places where direct dumping in and from shore spreads litter out to deep areas eased by meteorological phenomena and particular configurations of the continental margin (Pierdomenico et al., 2019).

Deep sea basins are, therefore, expected to act as litter accumulation sites, with potential adverse effects on low turnover, fragile deep sea ecosystems (Ramirez-Llodra et al., 2011; Angiolillo and Fortibuoni, 2020; Peng et al., 2020; Ramirez-Llodra, 2020; Canals et al., 2021). However, deep sea basins are a particularly challenging environment due to their inaccessibility and, often, to their remoteness and vastness as well. Access to the deep sea is costly and requires advanced technologies and approaches, which become more strict with increasing water depth (Pham et al., 2014; Fulton et al., 2019; Amon et al., 2020; Bajaj et al., 2021; Canals et al., 2021; Przeslawski and Christenhusz, 2022). The overall extent to which the deepest regions of ocean and sea basins accumulate marine litter is still unknown.

In this paper, we aim at responding to such a question for the deepest point in the land-locked Mediterranean Sea, thus improving current knowledge on deep seafloor littering. We took advantage of a unique observational opportunity to provide quantitative in situ data of marine macrolitter in the abyssal Calypso Deep to discuss the implications of the findings in terms of monitoring methodologies and scientific, policy and societal significance. The fact that Calypso Deep is offshore densely populated coastal areas and within a region with an intense maritime traffic added interest to its study in terms of seafloor macrolitter abundance. Overall, the importance of the macrolitter fraction in the total marine litter pool has been confirmed at global level (Kaandorp et al., 2023).

2. Study area

2.1. Geological setting

The Calypso Deep, also known as Oinousses Deep, Matapan-Vavilov Deep and Vavilov Deep, is located in the Hellenic Trench, in the eastern Ionian Sea, Eastern Mediterranean Basin, about 60 km west from the closest shoreline in the Peloponnese (Greece) (Fig. 1A, B). From now onwards, we will take its deepest inner part as a reference, to which we will refer as "inner Calypso Deep", as defined by the 5000 m depth contour. With reference coordinates 36°34′N and 21°08′E, the inner Calypso Deep contains the deepest point in the entire Mediterranean Sea, with a nominal depth of 5122 m, according to combined multibeam bathymetry and dive data from Caladan Oceanic and the Hellenic Centre for Marine Research (HCMR).

The Kefallonia NE-NNE/SW-SSW oriented strike-slip fault divides the eastern Ionian Sea into a northern and a southern segment. The southern segment, corresponding to the Hellenic Trench, stretches along 530 km from the Kefallonia Fault, west of the island of the same name, to the north, to the Ptolemy Seamounts south of Crete, to the south. The Hellenic Trench region is tectonically dynamic, with high seismicity. The seafloor morphology of the trench is, therefore, strongly controlled by active faulting, which results in a highly uneven terrain (Sakellariou and Alexandri, 2007). Also the intricate shape of the coastline along the Greek mainland in the Ionian Sea, including the large gulfs of Messiniakos and Lakonikos, and associated inland valleys, is of tectonic origin (Sakellariou and Tsampouraki-Kraounaki, 2019).

The Hellenic Trench encompasses a NW-SE oriented string of depressions of different shapes, most of them with depths in excess of 3000–4000 m, of which Calypso Deep, about 160 km south of the trench's northern limit, is the deepest one. These deep depressions form the largest area of warm abyssal environments on Earth, with near-bottom water temperatures of 13–14 °C or even higher (Roether et al., 1996; Linley et al., 2018), which contrast with typical temperatures of 2–4 °C in the main oceans' abyssal regions (Thistle, 2003).

The "broader Calypso Deep" occupies an area that descends in steps from the Peloponnese coast to the northeast (Fig. 1B). The largest of these steps, measuring 34 × 14 km and lying at a mean depth of 3000 m, is the one closer to the shoreline. The seafloor straight to the north, east and south of the inner Calypso Deep is also staggered and markedly uneven, with some prominent ridges and lows, locally suggesting an incipient, discontinuous submarine drainage system. The Peloponnese slope northeast and east of the broader Calypso Deep displays numerous, roughly parallel, up to 15 km long submarine canyons with their heads at 2–7 km from shore and their mouths at 2100–2800 m of depth depending on the specific canyon ((Sakellariou et al., 2022), numerical data from https://emodnet.ec.europa.eu/geoviewer/). West of the inner Calypso Deep, the seafloor presents a very different character, with a

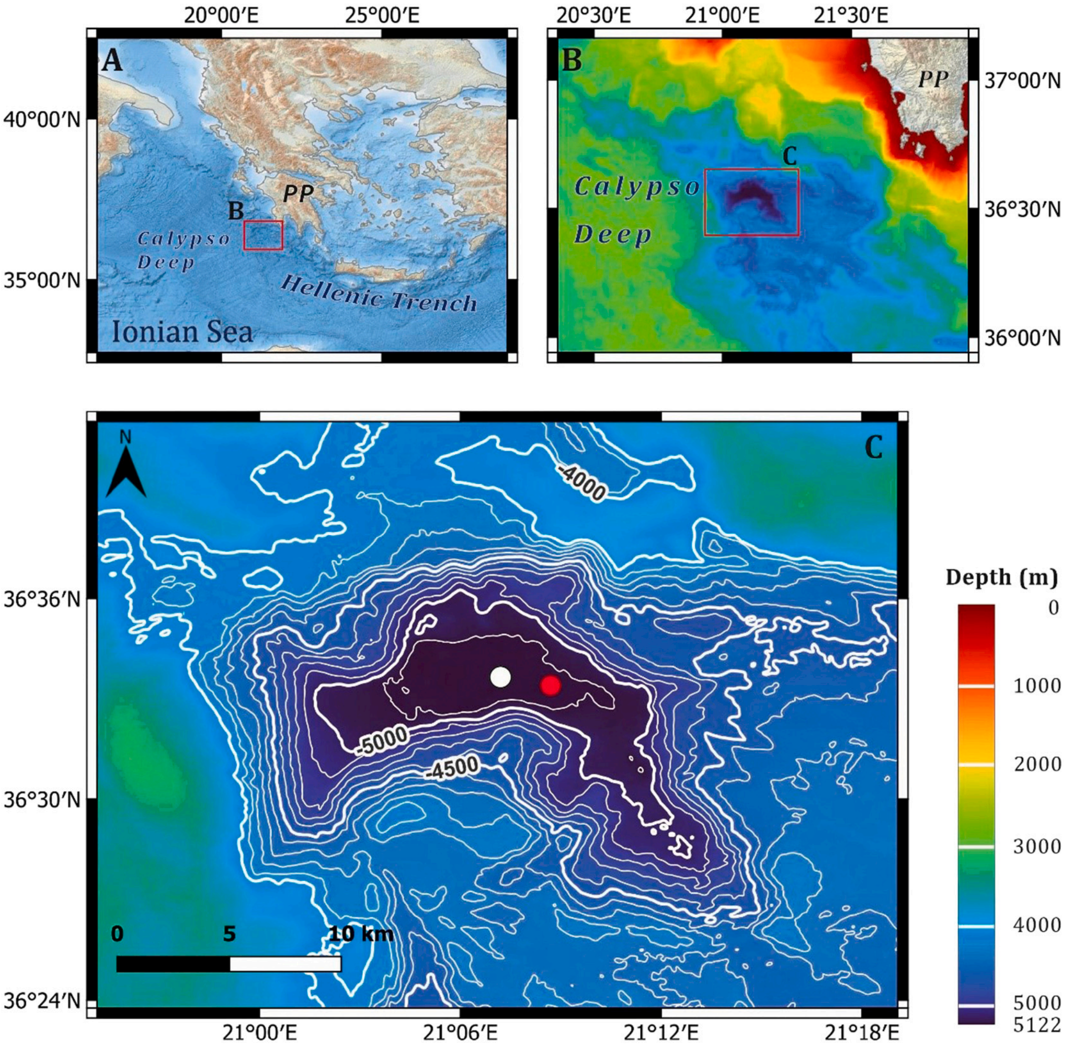

Fig. 1. (A) General location of the Calypso Deep (box) in the Ionian Sea. PP: Peloponnese Peninsula. (B) Close up and general bathymetry of Calypso Deep (box) and surrounding area. For depth ranges, see colour scale. (C) Detailed bathymetry of Calypso Deep with depth contours in meters. The position of the deepest point is indicated by the white dot, while the dive area is indicated by the red dot. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

highly uneven, lower height local relief sloping eastward from a subdued, roughly NNW-SSE oriented elevation (Fig. 1B). Such elevation actually is part of the Mediterranean Ridge, a regional, complex deformation feature encompassing folds and thrust, strike slip and normal faults (Polonia et al., 2011).

The above described physiography defines the broader Calypso Deep as a funnel-shaped feature roughly measuring 90 km from north to south and 70 km from west to east (Fig. 1C). Providing more precise areal values or exact boundaries is precluded because of the poor definition of a broader Calypso Deep outer rim, laying at depths from 2500 to 4000 m.

The smaller inner Calypso Deep is an 18 km long and 4 to 7 km across, flat-bottomed, kidney-shaped hole (Fig. 1C). The inner Calypso Deep itself is bounded by well-defined steep slopes to the north and west, with a rim at about 4000 m, whereas to the south and east there is no well-defined rim.

2.2. Sedimentation

Tectonics and associated fault movements determine the sedimentation in the region, with turbidites and other gravity driven deposits forming most of the sedimentary infill, according to Sakellariou and Tsampouraki-Kraounaki (2019). Northward of the Calypso Deep, highly disorganized sediments indicate mass-wasting processes (Camera, 2014). Moreover, crescent-shaped slide scars are clearly visible in the bathymetry, some of which coincide with or are very close to canyon heads, which points to slope instability as a relevant sedimentary process leading to the accumulation of mass wasting deposits (https://emodnet.ec.europa.eu/geoviewer/).

Sediments in the study area, and by extension in most of the deep Ionian Sea, form under a unique combination of environmental conditions resulting from extreme oligotrophy (Polymenakou et al., 2008), with low bottom-reaching particulate mass fluxes, and tectonics. Within this context, Stavrakakis and Lykousis (2011) illustrated temporal variations of mass fluxes at various depths. However, no correlation between mass fluxes, rain and river discharges was found, thus suggesting that other intervening factors —like atmospheric deposition, primary production events, and sediment resuspension— control particulate transfer to the deep.

In accordance to the above, the rate of sedimentation as derived from sediment cores collected at locations relatively close to the Calypso Deep is estimated to range between 1.6 and 2 cm/1000 yr (Dominik and Mangini, 1979). The highly oligotrophic character of the Eastern Mediterranean Basin is reflected by organic carbon (OC) contents in deep-sea sediments ranging from 0.07 to 1.55 % of the sediment dry weight (Polymenakou et al., 2008). In summary, sediments in the study area, and by extension in most of the deep Ionian Sea, form under a unique combination of environmental conditions resulting from extreme oligotrophy, high deep-water temperature at abyssal depths, and active tectonics.

2.3. Oceanography

Deep water in the Eastern Mediterranean Sea, including the Ionian Sea, forms in the Adriatic Sea and the Aegean Sea, with relative contributions that shift through time. This was observed in an unprecedented way in the early 90s when a major event, known as the Eastern Mediterranean Transient (EMT), involved a sharp change in the main deep water formation site from the Adriatic Sea to the Aegean Sea (Roether et al., 1996, 2007). A switch back to the pre-EMT regime has been noticed in the last years resulting from reduced deep water formation (Sisma-Ventura et al., 2021). Variability between Adriatic Deep Water (AdDW) and Aegean dense water formation and propagation determines, indeed, their relative contributions to the Eastern Mediterranean Deep Water (EMDW), the bottom water of the Eastern Mediterranean Sea (Bensi et al., 2013), i.e. the water mass in contact with the bottom of Calypso Deep.

In 2009 and 2011, baited cameras equipped with sensors were placed in both the broader and inner Calypso Deep (Linley et al., 2018). Temperature increased with depth beyond around 2000 m. Salinity remained stable below 1346 m. Current speeds were generally low, ranging from 3 to 8 cm/s at depths over 1346 m. An exception was recorded at the broader Calypso Deep, where a prolonged current speed of 17.9 cm/s in average was recorded (Table 1). This illustrates the occasional occurrence of deep water mass movements faster than background velocities, possibly involving local topographical influences and/or gravity-driven sedimentary processes.

Smedile et al. (2013) also observed higher amounts of particulate organic matter (POM) and dissolved organic carbon (DOC) in deep waters over Calypso Deep compared to nearby areas. This richness likely originates from surface waters and continental shelves. These authors attribute this contrast to the proximity of the coastline, affecting water circulation and water mass distribution.

CDT hydrographic stations and the sea water velocity data provided by Copernicus Marine Service and post processed in Ocean Data View (ODV) allow outlining water circulation and the distribution pattern of water masses in the broader study area. Root mean squared (RMS) sea current speed (m/s) and direction values showed that the currents flow to the northeast and north in the entire water column above Calypso Deep (Fig. 2).

The wider area, south of Calypso Deep, is characterized by high probability of occurrence of eddies and gyres (Bonaduce et al., 2021). It is well known that currents associated to these features cause floating litter to drift towards their centers, which then acts as garbage traps (Van Sebille et al., 2012; Zambianchi et al., 2014; Rodríguez-Díaz et al., 2020; Connan et al., 2021, and references therein).

Table 1
Environmental conditions recorded during baited camera deployments in the Calypso Deep, as reported in Linley et al. (2018).

Parameter	Broader Calypso Deep	Inner Calypso Deep
Coordinates	36.61898°N, 21.48337°E	36.55050°N, 21.11617°E
Date	14/12/2009	30/01/2011
Duration (h)	17.3	4.1
Water depth (m)	4204	5111
Average current (cm s^{-1})	17.9 ± 1.8	2.4 ± 0.82
Temperature (°C)	14.2	14.3
Salinity (PSU)	38.7	38.7

2.4. Biology

In the Calypso Deep, and more generally in the deep Ionian Sea, vertebrate and invertebrate fauna is highly impoverished. Baited cameras at depths larger than 3000 m, including Calypso Deep, attracted only one fish species, the Mediterranean grenadier, *Coryphaenoides mediterraneus* (3400–5111 m), extending this species' maximum recorded depth to 5111 m (Linley et al., 2018). The only invertebrate recorded in Calypso Deep was the dressed deep-sea shrimp, *Acanthephyra eximia* (1346–5111 m). These observations indicate that the density of bait-attending deep-sea organisms is very scarce compared to equivalent depths in other deep sea basins, such as those in the Atlantic Ocean (Linley et al., 2018). Low resource input and high temperature at depth (see above), together with possible colonization barriers, are the likely causes (Emig and Geistdoerfer, 2005; Linley et al., 2018). Those observations agree with the lack of visible biologically formed sedimentary structures (e.g. animal tracks and burrows, faecal casts) in an "exceptionally uniform" seabed in Calypso Deep, as reported by Linley et al. (2018), who also noticed that sediment becomes more uniform and animal burrows and tracks diminish with increasing depth. Prokaryotic diversity also is extremely poor in Calypso Deep, unlike any other deep-sea metagenome (Smedile et al., 2013).

Deep-sea fauna in the entire Eastern Mediterranean Sea is constrained by low-surface productivity, as is also the case over Calypso Deep despite the relative richness of POM and DOC in deep waters over this feature mentioned by Smedile et al. (2013). Chlorophyll concentrations in the Eastern Mediterranean are below 0.15 mg m^{-3}, which is less to much less than in the Western Mediterranean or the Northeast Atlantic (Raitsos et al., 2005; D'Ortenzio and Ribera d'Alcalà, 2008). It has been suggested that a large part of the organic inputs to the deep Eastern Mediterranean Sea may be land-derived (Van Santvoort et al., 2002). This was later confirmed for sediments from the deep Ionian Sea characterized by up to 64.2 % of terrestrial OC (Pedrosa-Pàmies et al., 2015; Pedrosa-Pàmies et al., 2016; Pedrosa-Pàmies et al., 2021). However, this would be insufficient to compensate the deficit in organic matter export from the poorly productive sea surface layer to the deep (Rex and Etter, 2010). Furthermore, the elevated water temperature (see above, including Table 1) steers microbial activity and the subsequent decaying of OC, which likely reduces even more the primary productivity fraction being able to reach the deep seafloor (Laws et al., 2000) while augmenting the metabolic rate of the animals inhabiting these food-starved environments (Clarke, 2004; Seibel and Drazen, 2007).

3. Materials and methods

3.1. Diving vehicle and dive parameters

On February 10, 2020, a descent into Calypso Deep was conducted using the fully certified manned and untethered Deep Submergence Vehicle (DSV) Limiting Factor by Triton Submarines (Jamieson et al., 2019) after the vehicle had visited the deepest points of all world's oceans under the leadership of Victor Vescovo (Young, 2020).

The dive to the Calypso Deep was performed by Victor Vescovo piloting and Prince Albert II of Monaco as passenger. They reached the bottom of the Calypso Deep at a depth of 5109 m ± 1 m as confirmed by multiple sensors, XBT corrected CTD data and two bottom landers. The survey was performed in the deepest part of the Calypso Deep, on a 56.6 km^2 flat plane below 5050 m depth, with its central part deeper than 5100 m and 29.1 km^2 in areal extent. During the submersible dive, which lasted 4 h and 20 min, 43 min were spent on the seafloor including an observation time of 36 min, during which ca. 850 m of distance were covered and surveyed. High-resolution videos were captured using three cameras with different angles of view (DeepSea Power & Light IP Multi SeaCam 3105 model, San Diego, USA).

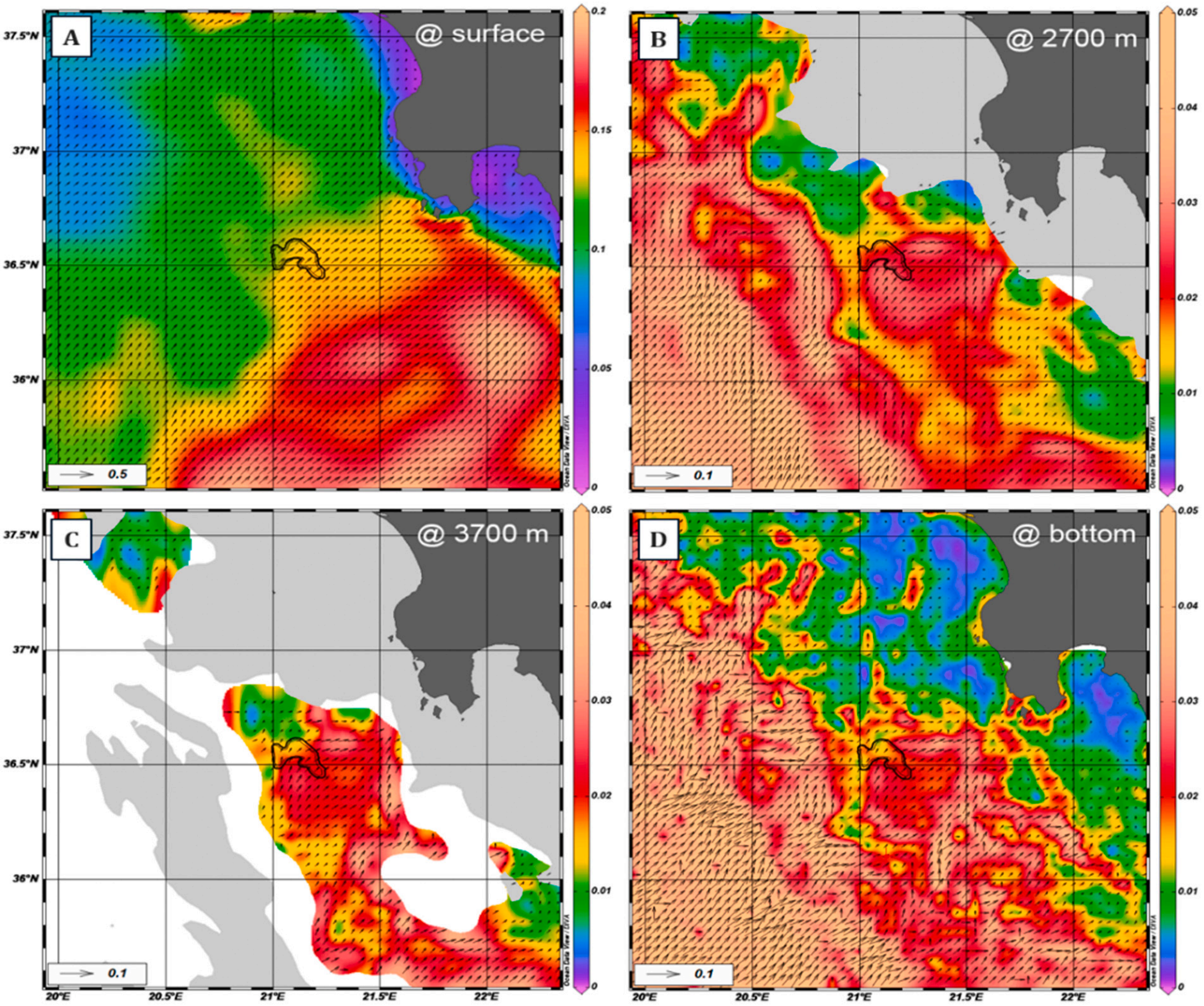

Fig. 2. Root mean squared (RMS) current speed (m/s) and direction values at (A) the sea surface, (B) 2700 m depth, (C) 3700 m depth, and (D) over the seafloor. The water circulation and the water masses distribution pattern in the wider area were predicted by the monthly means of the northward (vo) and eastward (uo) sea water velocities that have been acquired for all depth layers and for the last 10 years (2013–2023) from the Copernicus Marine Mediterranean Sea Physics Reanalysis product. The area and the location of inner Calypso Deep are also shown in the maps (kidney-shaped black line at the centre of the images).

3.2. Surveyed area

The surface area of the seabed covered by the survey was estimated by analysing 3D models generated after processing the footage with the Structure from Motion (SfM) photogrammetry technique (Price et al., 2019), as described below. Frame extraction was carried out for each of the videos recorded with the DSV at 0.25 s frequency. Frames with litter items of well-known size (i.e. beer cans, plastic bottles) as reference, were aligned using Reality Capture (Epic Games, North Carolina, USA) to generate 3D sparse point clouds (Figs. 3 and 4).

Point clouds for 6 subsections, covering ca. 7 % of the survey path, were scaled by referencing to the dimension of litter items with known sizes. The analysis of the full track, showing mostly a uniform speed pattern, confirmed the representativity of the selected sections when extrapolating the results to the entire survey track. The sparse point clouds were then reprocessed for calculating high density point clouds. Within each of the point clouds, the average camera field of view width and the distance between two items identified on the seafloor along the DSV moving direction were measured (Figs. 3 and 4). The number of frames between the two items was used to calculate the DSV moving time between these objects. The DSV velocity was then derived based on these two measurements. The average DSV velocity was subsequently obtained after averaging the DSV velocity calculated for each point cloud, resulting in 0.49 m/s (±0.03 m/s). Afterwards, the total distance covered with the DSV was calculated by multiplying the average velocity by the number of frames for which the DSV was moving during the survey (Fig. 5).

Videos were analyzed with the QGIS software to draw the DSV path. Approximately every 5 s the covered distance and the direction variation were estimated and drawn as a segment of a polyline, using a metric reference system (Fig. 5). The resulting total survey length was 850 ± 37 m, which corresponds to a straight distance of 650 m between the start and ending points.

The field of view width along the track depended on the height of the DSV above ground, which modified the exact size of the illuminated area. Changes in the visibility of the periphery of the observation field increased the uncertainty of the calculation of the imaged area. The width of the field of view was also calculated over six point clouds with litter items of known size to scale the models (Figs. 3 and 4). The obtained average width of the surveyed track was 6.52 ± 0.39 m.

The total area covered by the video survey of Calypso Deep was finally estimated by multiplying the total distance travelled by the average camera field of view width. The error associated with the measurements was estimated from the litter objects scaling error, finally resulting in a total surveyed area of 5540 ± 522 m^2.

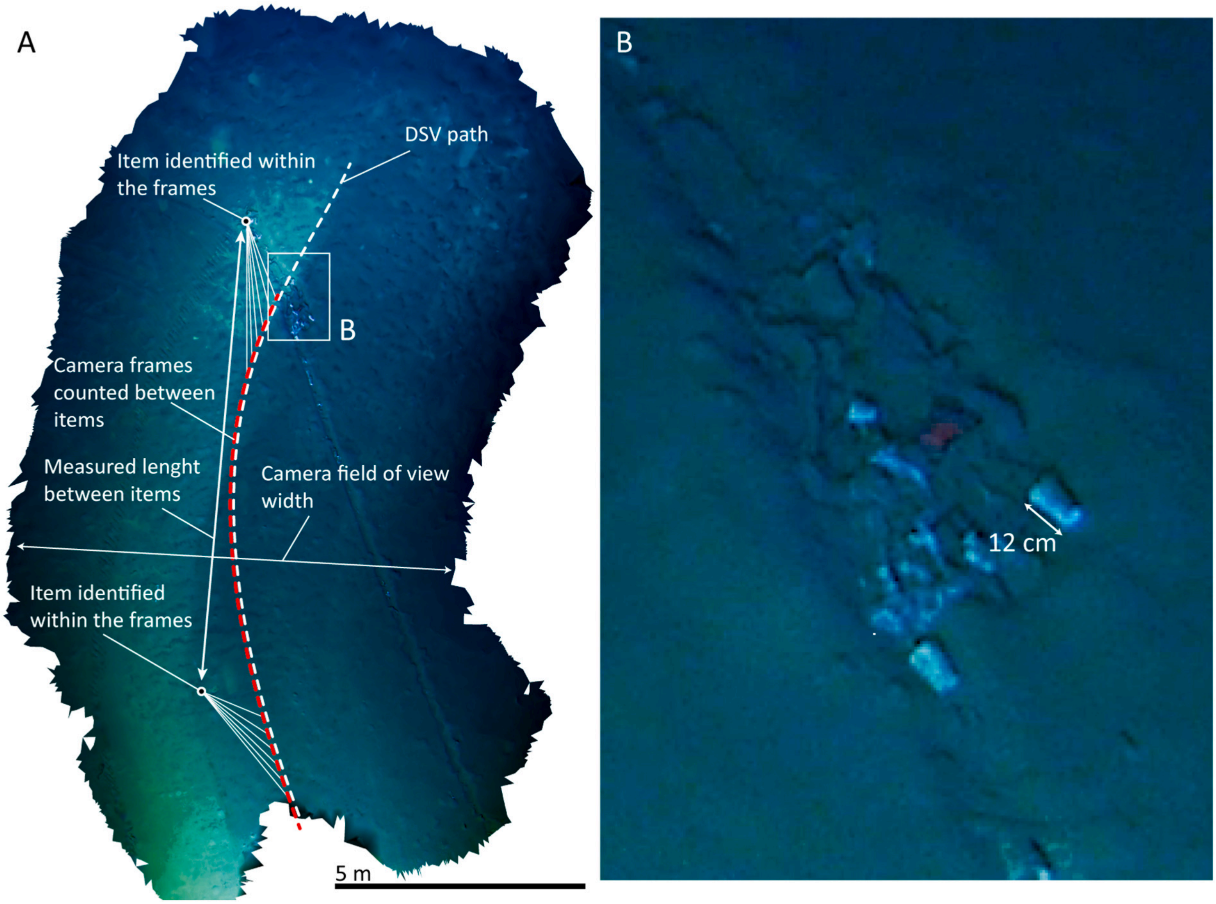

Fig. 3. (A) 3D model generated from a subset of video frames by reference to a litter item of known size shown in B. The white dashed line in A represents the camera frames along the Deep Submergence Vehicle (DSV) Limiting Factor moving path, whereas the red dashed line represents the frames counted between two items identified on the seabed. (B) Accumulation of litter items in the inner Calypso Deep with a litter item of known size (12 cm) used as a reference for 3D model generation (see main text for detailed explanation). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. Image analysis and object identification, category attribution and sizing

The recorded high resolution videos have been analyzed for macrolitter occurrence, aiming at the detection of objects equal or above a lower size range of 2.5 cm (largest extension), in line with provisions for the monitoring of marine macrolitter (MSFD Technical Group on Marine Litter, 2023). Litter items have been identified and tagged by their occurrence time during the dive. The views and perspectives from three different cameras where used for enhanced object identification.

Category attribution of the litter items followed the Joint List of Litter Categories (JLLC) developed by the Marine Strategy Framework Directive (MSFD) Technical Group on Marine Litter (Fleet et al., 2021). The JLLC combines previous lists and aims at identifying, classifying and documenting marine macrolitter items in an unambiguous way in order to enable comparable results. The list, which is based on material types and uses, follows an hierarchical approach, allows quantitative data analysis at large scale, and facilitates litter group quantifications and detailed analysis across environmental compartments.

It should be kept in mind that the identification and, ultimately, the quantitative assessment of seafloor macrolitter from video footage is sometimes challenging. While trawling techniques collect the litter items, allowing a closer inspection, they are destructive and highly selective in the collection of litter items, and also mix up all items in the net independently of where they were caught. Image based approaches instead generally have lower impact (e.g. in terms of harm to benthic communities and resuspension) and accurate positioning, but they provide limited object information depending on overall illumination of the seabed scene, view angles and optical resolution, and also prevent investigating the objects further.

Classification of every litter item imaged in the Calypso Deep included the tentative identification and attribution to an item category of the JLLC, assigning the item to a J-Code. Objects identified as litter items, but for which neither the material type nor the object category were known, were flagged as J0 objects. Objects that could be litter items, but which were not certainly identified as such were flagged as JX objects. The later items (JX) were not used for litter concentration calculations. Finally, individual objects were attributed to size classes, according to their the longest dimension.

The size of litter objects, including fragments and J0 items, was estimated by comparison with objects of known size found in the footage, which were used as references. For example, a 1.5 L plastic water bottle (34 cm) and a metal beverage can (12 cm) provided such size references (Fig. 6A, B). Object detectability changed considerably across the track, with a reduction towards the borders of the field of view.

Last but not least, the authors are fully aware of the limitations —but also the value— of the new dataset collected in Calypso Deep. Because of this reason we refrain going further in terms of statistical analyses.

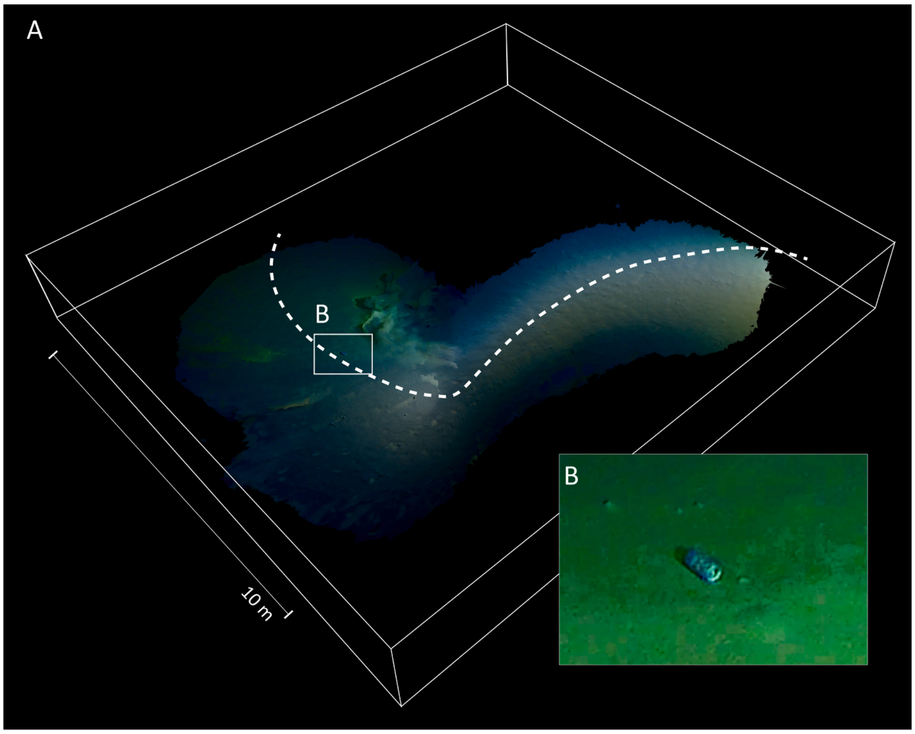

Fig. 4. (A) View of the observational path reconstructed using photogrammetry methods also showing the track of the Deep Submergence Vehicle (DSV) Limiting Factor (white dashed line). (B) Detail of the litter item used to scale the 3D model.

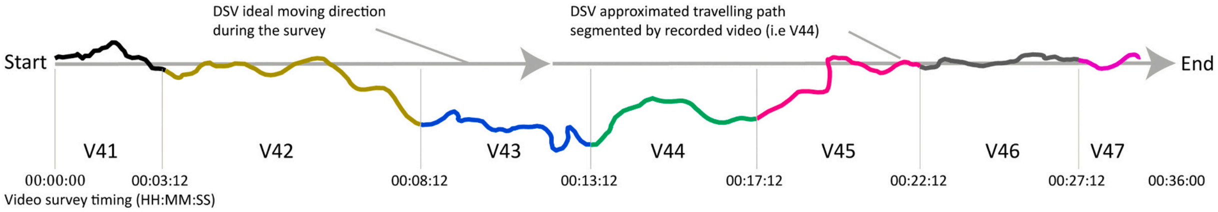

Fig. 5. Deep Submergence Vehicle (DSV) Limiting Factor path derived from video direction and covered distance analysis. The coding (V41 to V47) and colour scheme refers to the videos' survey timing recorded during the DSV dive from the starting point until the end. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

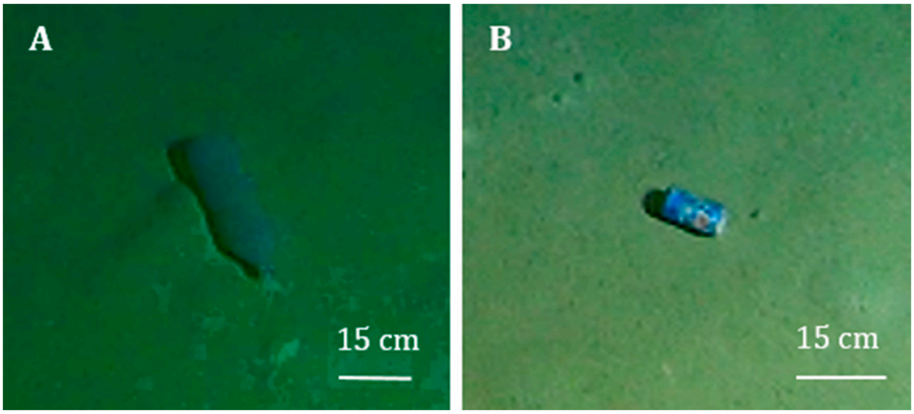

Fig. 6. (A) 1.5 L plastic water bottle used as size reference. Note sediment shadow to the left of the bottle. (B) Metal beverage can used as size reference.

4. Results

4.1. Litter classification

A total of 148 litter objects were observed on the survey videos, plus other 19 items that were suspected to be of anthropogenic origin, but could not be fully confirmed as such, thus totalling 167 items (Figs. 7 and 8, and Table 2). Among the identified litter objects, 67 (45 % of certain litter items, or 40.1 % of total items) have been attributed to JLLC categories (Fig. 9A, B, and Supplementary Table 1), whereas the other 81 objects (55 % of certain litter items, or 48.5 % of total items) could not be attributed to a specific litter category, in most cases because the object material type could not be confirmed (Fig. 9A). The 19 suspected, or potential, litter items represent 11.4 % of total items.

Most of the identified objects with category attribution per material type were plastics (88 %), while the rest consisted of glass, metal and paper.

4.2. Litter concentrations

The concentration of litter items on the observed seafloor area, as derived from the distance covered over the seafloor and the field of view (cf. Section 3), is expressed as Total Abundance of Litter Items/km^2. The total 148 certain litter items, with or without category attribution per material type, scattered across the 5540 ± 522 m^2 of the observed area result in a litter concentration of 26,715 litter items/km^2, or 267 items/ha, with an estimated uncertainty of ca. ±10 %, due to uncertainty in the litter identification, in the abyssal inner Calypso Deep.

Litter distribution along the transect was rather homogeneous, with one hotspot area of increased litter density at 598 m from the transect starting point (Figs. 10 and 11). If the litter hotspot is excluded as an outlier, the total number of objects identified during the survey is reduced to 124 items, resulting in a litter concentration of 22,383 items/km^2, or 224 items/ha, with an uncertainty of about ±10 %.

5. Discussion

Our results provide the first ever detailed quantification and identification of seafloor macrolitter in the deepest site of the Mediterranean Sea. The litter abundance found in the Calypso Deep, with 26,715 items/km^2 (or 267 items/ha) is among the highest ever recorded in a deep sea environment (Tables 3 and 4).

5.1. Comparison with other deep sea areas

Using a model built from data collected with a Remotely Operated Vehicle (ROV), it has been estimated that 3 to 11 million metric tonnes (MMT) of plastics resided on the ocean floor as of 2020 (Zhu et al., 2024). This is of similar magnitude to annual inputs from land and one to two orders of magnitude greater than what is predicted to be floating on the ocean surface. However, the number of studies on the ultradeep seafloor remains very limited, with sampling efforts to date concentrated in coastal marine environments.

Quantitative concentration analyses from large scale surveys in the Pacific Ocean showed plastic densities ranging from 17 to 335 items/km^2 at depths of 1092–5977 m (Chiba et al., 2018). The deepest published record was for a metal can at a depth of 7216 m in the Ryukyu Trench (Miyake et al., 2011). However, during one of his dives in June 2020 with DSV Limiting Factor into Challenger Deep –the deepest place on Earth–, in the Western Pacific Ocean, namely into the 10,923 ± 4 m Western Pool, Victor Vescovo reported finding white tether cable, composed of fiber optic cable and plastic (Young, 2020). On another

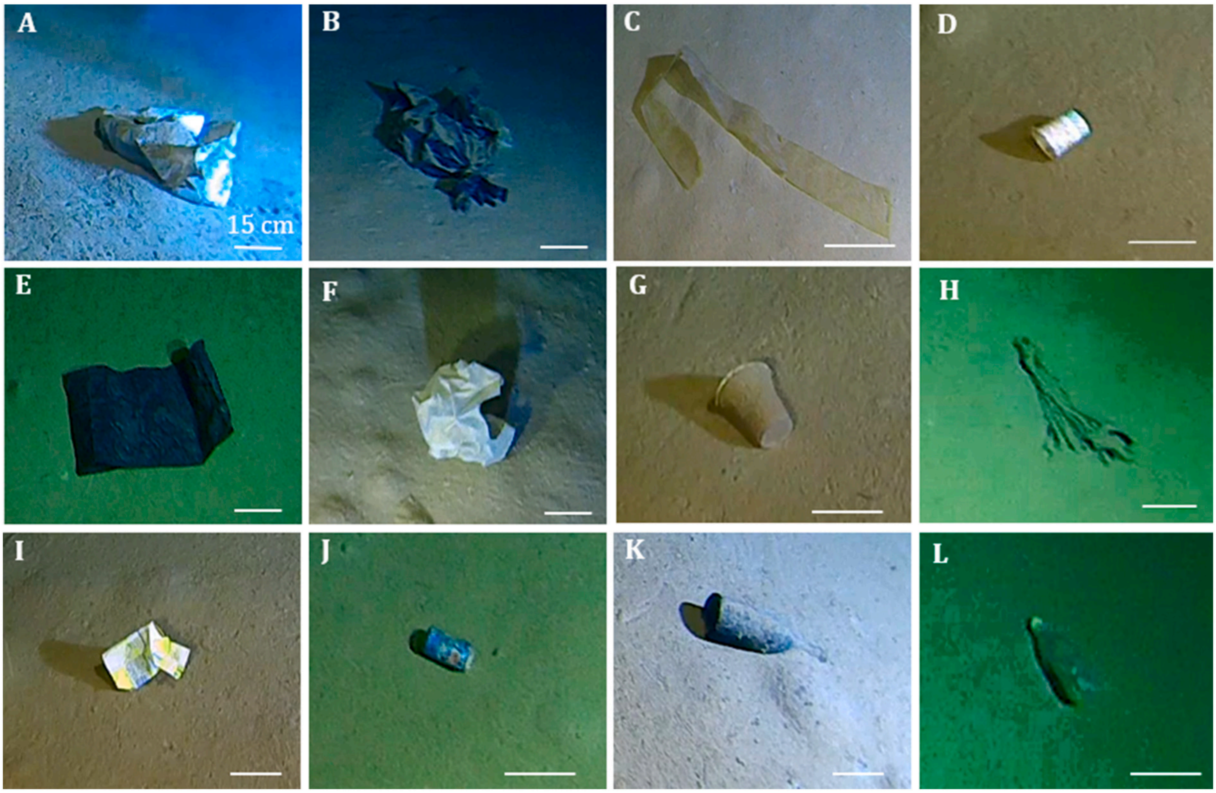

Fig. 7. Examples of identified litter items with category attribution per material type (cf. Table 2). (A) Plastic bag, J3. (B) Plastic heavy-duty sack, J36. (C) Plastic sheet, J67. (D) Plastic food container made of hard plastic, J225. (E) Plastic heavy-duty sack, J36. (F) Plastic bag, J3 (G) Cups and lids of hard plastic, J227. (H) Plastic rope > 1 cm in diameter, J49. (I) Paper cartons/Tetrapak (non-milk), J151. (J) Metal drink can, J175. (K) Glass bottle. Note sediment shadow with side scouring downwards of the bottle J200. (L) Plastic drink bottle ≤ 0.5 l, J7. J-codes according to Fleet et al. (2021). All scale bars are 15 cm.

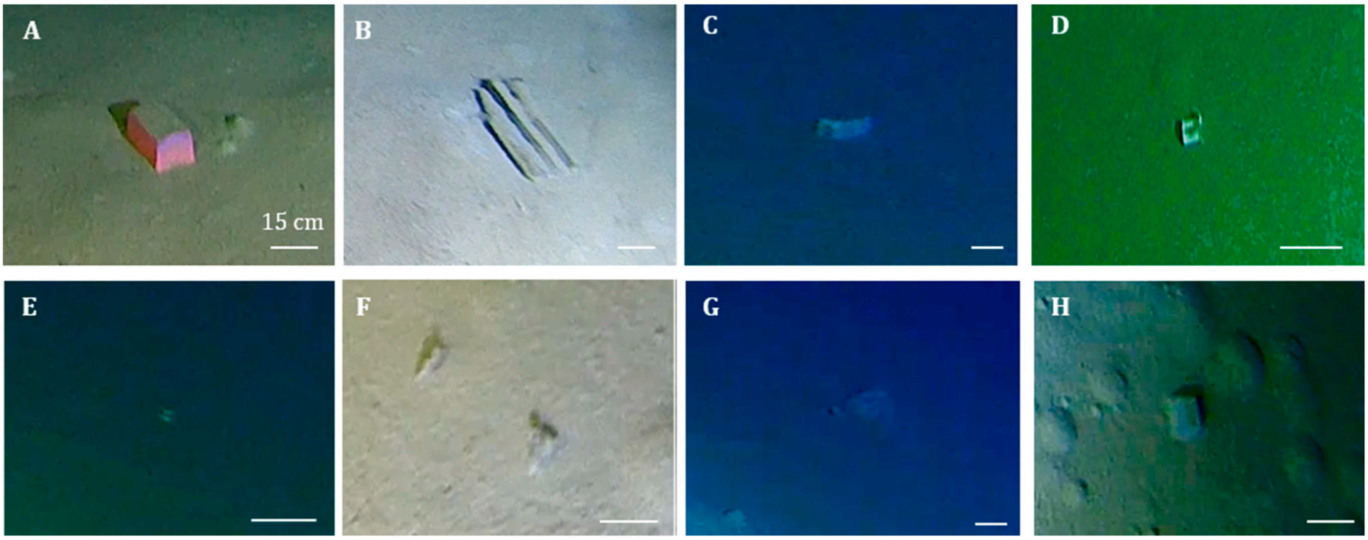

Fig. 8. Examples of litter items without category attribution (J0) per material type (A, B, C, D) and suspected, or potential, litter items (E, F, G, H). All scale bars are 15 cm.

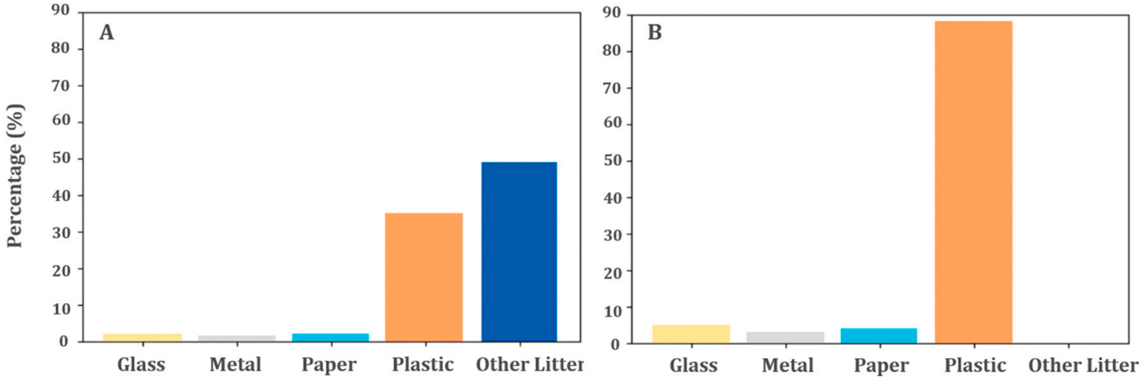

Fig. 9. (A) Distribution plot of total identified litter items including those with category attribution per material type, plus those without category attribution per material type, plus suspected, or potential, litter items. (B) Distribution plot of only identified litter items with category attribution per material type.

dive to the same Western Pool of Challenger Deep in June 2022, the DSV Limiting Factor recorded a glass beer bottle immediately after reaching the seafloor at an initial depth of 10,904 m (www.esri.com/en-us/industries/blog/articles/mission-accomplished-photos-from-the-challenger-deep-expedition).

To date, the largest deep-sea macrolitter densities were encountered in the South China Sea, with up to 36,818 items/km^2 and 51,929 items/km^2 in two submarine canyons (Peng et al., 2019); in the Fram Strait, North Atlantic Ocean, with 5351–8082 items/km^2 (Tekman et al., 2017); and in submarine canyons off the west coast of Portugal, also in the North Atlantic Ocean, with up to 6600 items/km^2 (Mordecai et al., 2011) (Table 3). The plastic fraction ranged from 25 to 68 % in previous studies, while it reaches 88 % in the current study. It is also to be noted that the values reported by Tekman et al. (2017) in the Fram Strait are far above the first quantitative assessment in 1999 and 2003 in the area (Galgani and Lecornu, 2004). The North West Pacific showed high macrolitter concentrations averaging 4883 items/km^2 in the Kuroshio Extension, as observed by HOV (Nakajima et al., 2021), and below 700 items/km^2 in the Kuril Kamchatka Trench after bottom trawl sampling (Abel et al., 2023). No macrolitter has been reported for the deep Antarctic Ocean —or Southern Ocean— until now, which is likely due to the lack of exploration efforts.

Marine litter in the abyssal domain of the Mediterranean Sea was first reported as bycatch from trawls conducted in 1995 in the Eastern Basin (Galil et al., 1995). In 1996, 1997 and 1998 pole trawling surveys sampled the Western Basin (Galgani et al., 2000), and reported on the composition of marine litter. The cruise Cylice in 1997 enabled the evaluation of seafloor litter by means of in situ imagery, using manned submersibles along four transects at depths below 2000 m (Galgani et al., 2000). Surveys conducted in 2000 (unpublished data) and in 2008–2012 (Ramirez-Llodra et al., 2013), reanalysed afterwards by Pham et al. (2014) and more recently by Angiolillo et al. (2021) in two canyons off Monaco and in the Gulf of Genoa, resulted in an overview of the distribution, density and composition of litter over a wide area, within a depth range from 2000 to 4616 m encompassing a noticeable variety of deep-water settings (Table 4).

Generally speaking, submarine canyons —as long cross-margin active transport pathways from shallow-waters to the abyss— were found to harbour higher litter concentrations and, therefore, it is unlikely that they are representative of the overall concentration of litter (and plastics) over broader areas (Galgani et al., 2019; Pham et al., 2014). In the deep Mediterranean Sea, Angiolillo et al. (2021) found that litter concentrations increased with depth and decreased with enhanced seafloor slope, thus explaining the high concentrations found in very deep areas in that basin (Ramirez-Llodra et al., 2013). These authors noticed that the most abundant litter types in the deep bathyal and abyssal environments of the Mediterranean Sea were plastics, glass, metal and clinker, the later mostly in sites located under the old shipping

Table 2
Classification of the identified litter items with category attribution recorded during the Deep Submergence Vehicle (DSV) Limiting Factor dive into inner Calypso Deep according to the Joint List of Litter Categories (JLLC) by Fleet et al. (2021), together with the total numbers of litter items without category attribution and suspected, or potential, litter items. Colours correspond to main material types (e.g. blue for paper, beige for glass, grey for metal, and orange for plastics). J-codes according to Fleet et al. (2021). See also Supplementary Table 1.

Ocurrence frequency in survey	J-code	Litter category name
2	J147	Paper bags
1	J151	Paper cartons/Tetrapak (non-milk)
2	J200	Glass bottles
1	J201	Glass jars
2	J175	Metal drink cans
17	J3	Plastic shopping/carrier/grocery bags
1	J7	Plastic drink bottles $\leq$ 0.5 l
1	J8	Plastic drink bottles $>$ 0.5 l
1	J18	Plastic crates, boxes, baskets
18	J36	Other plastic heavy-duty sacks
1	J49	Plastic rope (diameter $>$ 1 cm)
2	J67	Plastic sheets, industrial packaging, sheeting
1	J87	Plastic masking/duct/packing tape
1	J225	Plastic food containers made of hard non-foamed plastic
2	J226	Cups and cup lids of foamed polystyrene
14	J227	Cups and lids of hard plastic
Sum = 67		
81	J0	Litter item without category attribution
Sum = 148		
19	JX	Potential litter item
Sum = 167		

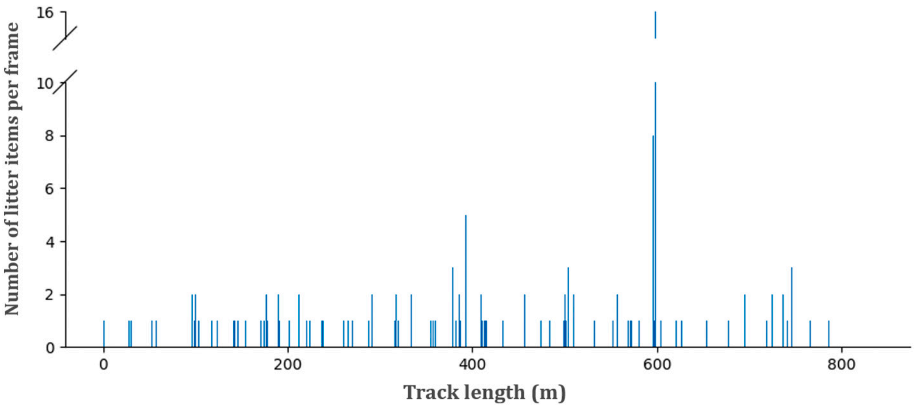

Fig. 10. Identified litter items distribution along the surveyed transect as number of items per image frame along the Deep Submergence Vehicle (DSV) Limiting Factor dive over the floor of inner Calypso Deep.

line connecting the Suez Canal with the Strait of Messina. In terms of litter mean weight at depths from 2000 to 3000 m, they did not find significant differences between the Western, Central, and Eastern regions of the Mediterranean Sea. Galil et al. (1995) and Galgani et al. (2000) mentioned, respectively, the high abundance of paint chips and clinker in some locations —up to 44 % along a transect from Suez Canal and up to 14.8 kg collected after three hauls in the Northwestern Mediterranean Sea, respectively—. Unfortunately, the different methodologies and quantification approaches applied (Table 4) prevent a comparative analysis of seafloor macro litter concentrations at depths below 2000 m in the Mediterranean Sea.

5.2. *Litter sources and accumulation mechanisms*

The concentration of litter in Calypso Deep is among the highest ever recorded in deep sea environments (Tables 3 and 4). Such a situation

Fig. 11. Litter hotspot along the dive of the Deep Submergence Vehicle (DSV) Limiting Factor over the floor of inner Calypso Deep. Note possible scouring with small levee formation to the sides of the litter trail.

Table 3

Seafloor macrolitter data from deep sea areas of the global ocean including the current study. Order is by litter concentration, from highest (above) to lowest (below). DSV: Deep Submergence Vehicle. ROV: Remotely Operated Vehicle (unmanned). *Calculated from litter items with category attribution per material type. **Without counting derelict fishing gear (nets and lines), which is mostly made of plastic (9.1–72.2 % in submarine canyons, and 10–87.5 % in seamounts).

Region	Method (number of dives/hauls/other)	Depth [m]	Litter concentration [items/km^2 unless otherwise stated]	Plastics (%)	References
South China Sea	ROV imagery (7/33.8 km)	1729–3378	<500 (but 36,818 and 51,929 in two canyons)	50	Peng et al. (2019)
Calypso Deep, Eastern Med Sea	DSV imagery (1)	~5122	26,715	88*	This study
Fram Strait, Atlantic-Arctic transition	Towed camera (1 transect, several years)	2400–2600	5351–8082	47	Tekman et al. (2017)
North West Pacific, Kuroshio Extension	DSV Imagery (3)	5700–5800	4883	77–100	Nakajima et al. (2021)
Submarine canyons west of Portugal	ROV imagery (16/60 km)	850–4574	417–6600	68	Mordecai et al. (2011)
Mid Atlantic Ocean	ROV imagery (5)	209–2318	59–556	25	Woodall et al. (2015)
European Atlantic Ocean and Med Sea	ROV imagery (35)	60–5552	930 (submarine canyons), 560 (seamounts), 390 (ocean ridges)	16.7–86.2 (subm. canyons), 5.9–19.5 (deep-basins)**	Pham et al. (2014)
Western North Pacific	ROV imagery	1092–5977	17–335	33	Chiba et al. (2018)
North West Pacific, Kuril-Kamchatka Trench	Agassiz trawl	8200–9852	219–619	–	Abel et al. (2023)
Gulf of Mexico	Otter trawl (40)	250–3650	140	40	Wei et al. (2012)
Fram Strait, Atlantic-Arctic transition	ROV imagery (10)	2500–5500	0.59/km	56	Galgani and Lecornu (2004)
North West Pacific, Kuril-Kamchatka	Agassiz trawl (12)	4870–5770	60 % of the litter items were from fishing	–	Fischer et al. (2015)
Antarctica	Agassiz trawl (37)	472–3213	0	–	Barnes et al. (2010)

deserves an explanation, both in terms of sources and accumulation mechanisms.

The Mediterranean Sea is a land-locked basin with (i) high population densities along most of its shores, (ii) a heavy touristic load mainly during summer months, (iii) a dense maritime traffic mostly from the Suez Channel to Gibraltar Strait, and vice versa, and (iv) fishing activities at different scales almost everywhere (e.g. Tubau et al., 2015). All of this involves associated anthropogenic pressures, both land-based and sea-based, including littering.

30 % of global maritime traffic passes through the Mediterranean along the way from Suez Canal to Gibraltar and the other way rounds (UNEP, 2015). The main route passes close to Calypso Deep, whereas the route towards the Adriatic Sea passes directly over Calypso Deep (Liubartseva et al., 2018). These authors indicate the existence of a convergence zone for floating debris in the Ionian Sea, in which north-eastern part is Calypso Deep. While deep-sea circulation in the Mediterranean remains poorly understood, this convergence zone receives substantial amounts of debris from the Adriatic Sea and the eastern and southern Mediterranean shores, largely due to persistent infrastructure deficiencies leading to litter release into the sea in the latter case (Mankou-Haddadi et al., 2021).

The currents in the entire water column over the Calypso Deep move predominantly north-east and northwards, potentially bringing floating litter items from the southern Ionian Sea and further south. The high possibility of occurrence of eddies in the wider area suggests that floating litter tends to concentrate in the area over Calypso Deep. It has also been observed that surface currents occasionally flow to the south transporting floating litter from the southern Adriatic Sea, Northwestern Greece and the mouth of Otranto Straits (Ferentinos and Kastanos, 1988; Astraldi et al., 1999).

Once into the sea, two key concepts emerge to explain the high concentrations of mostly light litter found in Calypso Deep, which are “drifting” and “sinking”. Previous studies have found concentrations of 50 to 500 g km^{-2} of plastic debris in surface waters of the eastern Ionian

Table 4

Seafloor litter in the deep Mediterranean Sea after different sources, ordered according to publication year. *Includes the Western, Central and Eastern Mediterranean basins. **59 % paint chips. ***44 % paint chips. $^+$Calculated from litter items with category attribution per material type. AT: Agassiz trawl. CB: Central Mediterranean Basin. EB: Eastern Mediterranean Basin. GoG: Gulf of Genoa. MLC: Mean litter concentration. MT: Maireta trawl. n/a: not available. Obs.: Observations. VT: Video transect. WB: Western Mediterranean Basin.

Place	Gear (number of hauls/transects)	Observation year	Depth (m)	Lower litter size limit (cm)	Number of litter samples/objects	Total area covered (km^2) or distance (km)	Samples/transects with litter (%)	MLC (items km^{-2} unless otherwise stated)	Max. observed (items km^{-2} unless otherwise stated)	Sample/transects with plastics (%)	Plastics (%)	Haul with litter from fishing (%)	Litter from fishing (%)	References
Eastern Basin	AT (4)	1995	2387–4616	1	92	0.015	100	22.3	22,413**	100	36***	n/a	n/a	Galil et al. (1995)
Gulf of Lion	AT (3)	1997	2220–2510	1	66	0.0061	66	10,800	25,500**	66	65	33	6	Galgani et al. (2000)
Off Corsica	VT (4)	1997	1746–2782	>2.5	40	23.23 km	100	1,72 km^{-1}	5.03 km^{-1}	n/a	n/a	–	n/a	Galgani et al. (2000)
Off NW Corsica	AT (7)	2000	2000–2661	1	216	0.067	100	3223	5454	100	81	100	6.5	
Med Sea*	MT (10), AT (4)	2008–2012	2000–3000	1.2	n/a	n/a	100	115–265 kg km^{-2}	3264.6 kg km^{-2}	100 WB 80 EB	<50	10–22	n/a	Ramirez-Llodra et al. (2013)
Med Sea*	MT (8)	2009	2883–3000	1.2	211	0.031	100	120–170 kg km^{-2}	3264.6 kg km^{-2}	100	19.5 EB	n/a	0.5 CB 16 WB	Pham et al. (2014)
Off Monaco and GoG	VT (2)	2018	1291–2194	>2.5	215	10.5 km	100	6.66 km^{-1}	16.4 km^{-1}	100	57	–	4.3	Angiolillo et al. (2021)
Calypso Deep	VT (1)	2020	~5122	>2.5	167	0.0055 0.65 km	100	26,715	26,715	100	88$^+$	–	n/a	This study

Sea, which are noticeable though not the highest in the Mediterranean Sea (Cózar et al., 2015). Sea surface currents in the eastern Ionian Sea, where Calypso Deep is, would mostly carry floating litter from the south (i.e. from the Peloponnese, Crete and beyond) but also from the North Aegean Sea (Politikos et al., 2017) (Fig. 2). This southern flow moves further northward along the coastline of Albania, Montenegro and Croatia, thus forming one of the main branches (the Eastern Adriatic Current) of the anticlockwise surface circulation of the Adriatic Sea (Lipizer et al., 2014). Subsurface currents, instead, would eventually carry floating litter from the north, off the mouth of Otranto Straits, i.e. from the southern Adriatic Sea and northwestern Greece (Fig. 2) (Ferentinos and Kastanos, 1988; Astraldi et al., 1999).

The above views are further supported by a simulated drift of floating litter originated from the south-eastern Ionian Sea over 2011–2014 using a coupled hydrodynamic-particle tracking model (Politikos et al., 2020). The model showed that the bulk of litter would eventually be transported offshore and partially out of the south-eastern Ionian Sea, after remaining at coastal sites for one to three months and partially travelling northward along the Peloponnese coast (i.e. over Calypso Deep) to the region around Corfu Island, which appears as a potential retention area, about 300 km north of Calypso Deep (Politikos et al., 2020). The observation that long-lived debris, including macrolitter items, dominate the global mass of buoyant marine litter (Kaandorp et al., 2023) fits with the observations made in the Calypso Deep floor where plastics, presumably long-lived, constitute the dominant fraction.

Even though the exact pathways of marine litter and deposition patterns on the seafloor are not yet fully understood, evidence indicates that large-scale seafloor depressions, like submarine canyons, deep sea trenches and other deepened areas, such as Calypso Deep, likely act as traps and ultimate sinks for light mobile litter, namely plastic material (Pham et al., 2014; Shimanaga and Yanagi, 2016; Hernandez et al., 2022; Pierdomenico et al., 2023). In the particular case of our study, it looks likely that the short distance to shore (60 km) also plays a role for light litter escaping from the coastal compartment to reach Calypso Deep (Fig. 1A, B).

Obviously, the prevailing near-bottom very low current speeds in the inner Calypso Deep (Table 1) would ease the ultimate settling of light litter and sedimentary particles in suspension, as evinced not only by the high concentration of debris in the Deep's floor but also by the very fine texture of the sediments there, with no single evidence of current induced bedforms but showing clusters of well-preserved small mounds of likely biological origin (Fig. 12).

However, the slight currents within the inner Calypso Deep are enough to keep moving the lightest litter items, which in that way would be redistributed across the Deep's floor before getting partly or totally buried or disintegrated into smaller pieces. This is well illustrated by a plastic bag, which was observed moving on the seafloor (Fig. 13). The flatness of the Calypso Deep would further facilitate the wandering of the lightest litter all across its rather extensive floor (cf. Section 3.2).

The dive into the inner Calypso Deep also illustrated what likely is the result of the direct dumping of a filled trash bag from a vessel. The alignment of different litter items in Fig. 11, with a wider central segment holding more items and two trails to one side and the opposite correspond to the “litter hotspot” at 598 m linear track distance in Fig. 10. The plastic bag itself possibly broke in smaller pieces as a consequence of the impact or later on, which dispersed subsequently.

After the observations made, and the interpretation above, it appears that litter on the bottom of the Calypso Deep originated from different sea and land based sources, including long range sea transport and direct dumping.

The very low sedimentation rates reported by near-bottom traps and sediment core analyses (cf. Section 2.2) support the view that sizeable litter at Calypso Deep will hardly get totally, or even partially, buried (Figs. 7G, H, K, 8 and 11). Only very thin sediment films on litter surfaces evidence sedimentation of marine snow and litter immobility. Small-scale (cm) morphological features, such as scouring, crevices and

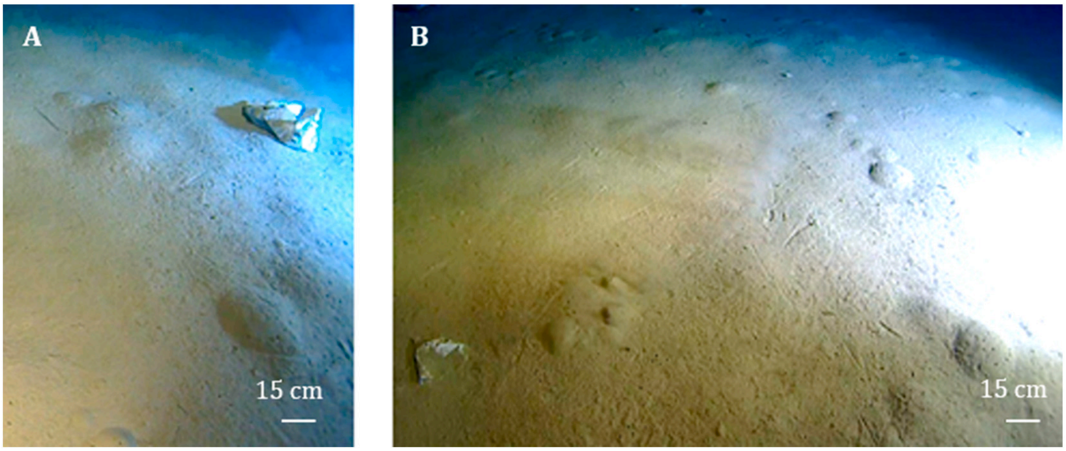

Fig. 12. Mounds on the seafloor of the inner Calypso Deep likely due to biological activity. Note the presence of litter items besides the mounds in (A) and on the lower left corner in (B).

Fig. 13. Plastic bag tumbling on the floor of inner Calypso Deep. Note the presence of abundant small mounds of likely biological origin.

sediment accumulations attached to litter items (Figs. 6A, 7K and 11) can be interpreted either as pre-existing features or as resulting from erosion by hard litter items on the soft bottom.

5.3. *Litter impacts*

As evinced in the video footage, the abundant litter found in the Calypso Deep floor constitutes a direct and persistent disturbance of its natural status (e.g. Figs. 11, 12 and 13). At first glance, it becomes obvious that litter accumulation is drastically changing the micromorphology of the seafloor, either by itself or by inducing local sediment accumulation and scouring due to the obstacle effect under the influence of bottom currents, even if mostly weak (cf. Section 5.2). Such changes have a potential to alter the habitat conditions while also facilitating further litter accumulation on the artificially induced new bottom features.

We didn't observe in the footage any kind of direct litter interactions with deep sea biota, either in terms of usage (i.e. for hiding) or colonization by organisms, contrary to what has been found in other marine settings (e.g. Aymà et al., 2014; Canals et al., 2021, and references therein). Likely, this is due to the highly impoverished vertebrate and invertebrate fauna in the deep Ionian Sea, and in Calypso Deep in particular (cf. Section 2.4), which could make, for instance, hiding essentially unnecessary. The dominant soft nature of most litter items (plastics) found there could also prevent some organisms to settle. Otherwise, the scarcity of geological and biological features in the Calypso Deep floor may convert at least some litter items as attractive spots for the rare crustacean and fish species observed there (cf. Section 2.4), even though their behaviour as related to litter is unknown. Litter can potentially provide a substrate for microbial communities, which otherwise would not occur in a given environment, or ease the spreading of existing ones, as already observed mainly in floating and shallow water debris (Kiessling et al., 2015; McGlade et al., 2024). Such a new marine microbial habitat is knowns as the “plastisphere”.

It is beyond the aims and possibilities of our study to assess potential harmful effects on organisms due to ingestion or to chemical additives in plastics and other litter categories occurring in the Calypso Deep. However, this does not preclude such effects to exist on still unknown or cryptic lifeforms, as suggested by the small mounds of probable biological origin imaged in our footage (Figs. 12 and 13).

Littering of Calypso Deep —with subsequent impacts— is likely to continue in the years ahead as suggested, first, by the current situation and, second, because the Mediterranean Sea as a whole is one of the greatest accumulation regions of floating plastic debris in the world ocean, part of which will ultimately settle to the basin floor. According to Cózar et al. (2015), the average density of floating plastics (1 item/4 m^2), as well as its occurrence in all sites sampled during their study, make the Mediterranean Sea comparable to the large ocean "garbage patches" or accumulation zones of the five subtropical ocean gyres. The same authors highlight that the proportion of large plastic debris —such as those dominating litter composition in Calypso Deep (Fig. 9 and Table 2)— in the surface waters of the Mediterranean Sea is higher than in oceanic gyres, which would be a consequence of the closer geographical connection with litter sources together with the high human pressure and the hydrodynamics of this semi-enclosed basin (cf. Section 5.2 and references therein).

5.4. *Methodological considerations on seafloor macrolitter detection and quantification using Human Occupied Vehicles*

The Calypso Deep dive with the DSV Limiting Factor as a platform for deep sea research has shown Human Occupied Vehicles (HOVs) capabilities and virtues, including their present (and future) role in seafloor monitoring. Besides ROVs, Autonomous Underwater Vehicles (AUVs) and towed cameras, HOVs enable direct observation, acquisition of high resolution imagery and, eventually, in situ accurate sampling. HOVs, while being costly and bringing human observers on-site, have the additional advantage of enhanced spatial and situational awareness, such as easing real time adjustment of survey strategies and distinct manoeuvring precision. Direct observations from underwater vehicles, either manned or unmanned, tethered or untethered, provide a unique way to quantify, identify and map seafloor features including litter.

The quantification, i.e. the identification and counting of litter items/unit area, of seafloor macrolitter in a comparable way still needs further development (Canals et al., 2021). Methodologies to derive litter category concentrations on the seafloor from non-photogrammetric still images and videos require calibration and estimation approaches to reduce uncertainty. Uncertainty in the quantifications will determine the ability for trend detection, which is essential in understanding input shifts and, eventually, in verifying the success of policy measures in the long term (cf. Section 5.5).

Further efforts are needed in order to facilitate (automate) the analysis of video imagery and still photography, including through artificial intelligence approaches, to derive quantitative assessments that would enable trend evaluation through multiple observations over time. Common evaluation criteria, litter item identification approaches and quantification methods are needed to enable the uptake of such data in large scale databases, in order to provide quality controlled and comparable data (Canals et al., 2021).

5.5. *Policy implications*

The confirmation of elevated concentrations of macrolitter in the abyssal regions of the European Seas should be seen in the context of current efforts to mitigate impacts from marine litter on the environment through the Marine Strategy Framework Directive, the EU Plastics Strategy, and the EU Zero Pollution Action Plan, as well as through regional activities, in particular the Mediterranean Action Plan.

With the apparent inability to clean the floor of the ocean from litter, for practical and cost reasons, the urgency of action and the need to prevent littering need to be furthermore emphasized, even while major efforts for reducing plastic consumption and moving towards circular economy are underway. Monitoring deep sea environments with harmonized methods that enable trend monitoring is required to verify the success of policy action and their implementation.

Litter on the bottom of the Calypso Deep likely originates from different sea and land-based sources, including long range transport (cf. Section 5.2). Finding of elevated litter concentrations in the deepest Mediterranean seafloor clearly indicates the need for large scale policy actions, at basin scale, to reduce litter input.

Likewise we can assume that the abyssal and hadal areas of the planet are all exposed to litter input and are accumulating the still incoming litter, providing final sinks and altering seabed small-scale morphology as well as deep sea habitats. This denotes that quantification and trend assessments of litter in the deep sea environments should be undertaken by harmonized methodologies to enable environmental assessments and targeted policy action.

The upcoming Global Treaty on Plastic Pollution (UN, 2023a) and the UN Agreement on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (UN, 2023b) are new and strong global policy tools, which should be implemented in a way to also protect the deep sea ocean environment. In terms of societal perception, the strong presence of marine litter in the deepest, often remote, and highly vulnerable areas of the global deep ocean has a considerable effect within the current discussion on planetary health and sustained ocean protection.

6. Conclusions

The presence of abundant litter in the deepest point of the Mediterranean Sea, namely the Calypso Deep, in the Ionian Sea, indicates that there is no place in the deep ocean devoid of such anthropogenic pollution. In fact, the calculated litter concentration expressed as items/km^2 is the second highest (26,715 items/km^2) known to date in the deep ocean (i.e. deeper than 2000 m).

Litter in the Calypso Deep is largely dominated by plastic items, which are lightweight and very easy to transport by marine currents. Sinking of plastics to the bottom of the ocean is eased by a number of processes including biofouling, ballasting and scavenging. Other secondary litter categories in terms of material type are made of glass, metal and paper. A significant amount of total alien objects on the floor of Calypso Deep could not be identified in terms of material type (49 % of total litter and suspected litter items).

Most litter arrives to the Calypso Deep mainly as sea surface floating debris, with likely subsurface contributions, both from southern and northern sources. Southern sources appear to be the most relevant ones. Strong indication of direct dumping from vessels has been also found, as evinced by a litter hotspot likely corresponding to a garbage bag.

No interactions between litter and the rare crustacean and fish species reported in Calypso Deep have been observed, which could be due directly to macrofaunal scarcity and/or to the limited duration and spatial span of our video footage. The hard-surfaced litter items though have a high potential to alter the soft-bottom character for this kind of deep sea habitats.

The only signs of biological activity in the Calypso Deep floor consist of numerous, small sized mounds with litter items scattered across them. No extensive bedforms indicative of the occurrence of bottom currents, able to transport sedimentary particles, have been found. However, associated to some litter items local sediment shadows (tails) and scours have been observed in the Calypso Deep soft bottom, likely due to the down current obstacle effect.

Our study demonstrates the capabilities of HOVs to undertake in situ inspection of the poorly known, and often highly remote and vulnerable, deepest ocean regions for scientific purposes, eventually side to side with other goals (e.g. technical or exploratory). It highlights aspects of ocean observation, which still leaves the deep sea, its biodiversity, natural processes and anthropogenic disturbances, mostly unobserved. This denotes that we do not have a clear indication of the quantities of litter on the deep seabed, which may significantly alter (to the worse) our projections and estimates about the ML quantities that are present in the Ocean.

Finally, while providing evidence of how far litter has reached already, our research supports on-going and future policy actions to urgently reduce the littering of the global ocean while preserving the unique ecosystems it hosts, from the shoreline to the hadal regions. Our findings hold a strong message to the society in terms of consumption habits, waste disposal, environmental consciousness and the urgent need for action, also keeping in mind eventual conflicts which could hinder mitigation measures, to preserve our planet, with our oceans and seas, for future generations.

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CRediT authorship contribution statement

Georg Hanke: Writing – original draft, Supervision, Project administration, Conceptualization. **Miquel Canals:** Writing – original draft, Conceptualization. **Victor Vescovo:** Methodology. **Tim MacDonald:** Methodology. **Eirini Martini:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Luis F. Ruiz-Orejón:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Francois Galgani:** Writing – original draft, Conceptualization. **Marco Palma:** Writing – original draft, Methodology, Investigation. **George Papatheodorou:** Writing – original draft. **Christos Ioakeimidis:** Writing – review & editing, Writing – original draft. **Dimitris Sakellariou:** Data curation. **Paraskevi Drakopoulou:** Data curation. **Elias Fakiris:** Data curation.

Disclaimer

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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.

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Data availability

Data will be made available on request.

References

Abalansa, S., El Mahrad, B., Vondolia, G.K., Icely, J., Newton, A., 2020. The marine plastic litter issue: a social-economic analysis. Sustainability 12, 8677. URL: https://www.mdpi.com/2071-1050/12/20/8677 https://doi.org/10.3390/su12208677.

Abel, S., Wu, F., Primpke, S., Gerdts, G., Brandt, A., 2023. Journey to the deep: plastic pollution in the hadal of deep-sea trenches. Environ. Pollut. 333, 122078. URL: https://www.sciencedirect.com/science/article/pii/S0269749123010801 https://doi.org/10.1016/j.envpol.2023.122078.

Amon, D.J., Kennedy, B.R.C., Cantwell, K., Suhre, K., Glickson, D., Shank, T.M., Rotjan, R.D., 2020. Deep-sea debris in the central and western Pacific Ocean. Frontiers in Marine Science 7, 369. URL: https://www.frontiersin.org/article/10.3389/fmars.2020.00369/full https://doi.org/10.3389/fmars.2020.00369.

Angiolillo, M., Fortibuoni, T., 2020. Impacts of marine litter on Mediterranean reef systems: from shallow to deep waters. Frontiers in Marine Science 7, 581966. URL: https://www.frontiersin.org/article/10.3389/fmars.2020.581966/full https://doi.org/10.3389/fmars.2020.581966.

Angiolillo, M., Gérigny, O., Valente, T., Fabri, M.C., Tambute, E., Rouanet, E., Claro, F., Tunesi, L., Vissio, A., Daniel, B., Galgani, F., 2021. Distribution of seafloor litter and its interaction with benthic organisms in deep waters of the Ligurian Sea (Northwestern Mediterranean). Sci. Total Environ. 788, 147745. URL: https://linkinghub.elsevier.com/retrieve/pii/S0048969721028163 https://doi.org/10.1016/j.scitotenv.2021.147745.

Astraldi, M., Balopoulos, S., Candela, J., Font, J., Gacic, M., Gasparini, G., Manca, B., Theocharis, A., Tintoré, J., 1999. The role of straits and channels in understanding the characteristics of Mediterranean circulation. Prog. Oceanogr. 44, 65–108. URL: https://linkinghub.elsevier.com/retrieve/pii/S007966119900021X https://doi.org/10.1016/S0079-6611(99)00021-X.

Aymà, A., Aguzzi, J., Company, J.B., Lastras, G., Mecho, A., 2014. Deep-sea fauna usae of marine litter. Deep-Sea Life 4.

Bajaj, R., Kulkarni, N., Raut, R., Garg, S., 2021. Sea debris: a review of marine litter detection techniques. International Journal of Innovative Research in Technology 7, 119–125.

Barnes, D.K., Walters, A., Gonçalves, L., 2010. Macroplastics at sea around Antarctica. Mar. Environ. Res. 70, 250–252. URL: https://linkinghub.elsevier.com/retrieve/pii/S0141113610000735 https://doi.org/10.1016/j.marenvres.2010.05.006.

Bellou, N., Gambardella, C., Karantzalos, K., Monteiro, J.G., Canning-Clode, J., Kemna, S., Arrieta-Giron, C.A., Lemmen, C., 2021. Global assessment of innovative solutions to tackle marine litter. Nature Sustainability 4, 516–524. URL: https://www.nature.com/articles/s41893-021-00726-2 https://doi.org/10.1038/s41893-021-00726-2.

Bensi, M., Rubino, A., Cardin, V., Hainbucher, D., Mancero-Mosquera, I., 2013. Structure and variability of the abyssal water masses in the Ionian Sea in the period 2003–2010. J. Geophys. Res. Oceans 118, 931–943. URL: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2012JC008178 https://doi.org/10.1029/2012JC008178.

Bergmann, M., Tekman, M.B., Gutow, L., 2017. LITTERBASE: an online portal for marine litter and microplastics and their implications for marine life. In: Baztan, J., Jorgensen, B., Pahl, S., Thompson, R., Vanderlinden, J.P. (Eds.), Fate and Impact of Microplastics in Marine Ecosystems (MICRO 2016). Elsevier, Amsterdam (The Netherlands).

Bonaduce, A., Cipollone, A., Johannessen, J.A., Staneva, J., Raj, R.P., Aydogdu, A., 2021. Ocean mesoscale variability: a case study on the Mediterranean Sea from a re-analysis perspective. Frontiers in Earth Science 9, 724879. URL: https://www.frontiersin.org/articles/10.3389/feart.2021.724879/full https://doi.org/10.3389/feart.2021.724879.

Camera, L., 2014. The Peloponnese Continental Margin from Zakynthos Island to Pylos: Morphology and Recent Sedimentary Processes. URL:. https://doi.org/10.4430/bgta0092.

Canals, M., Pham, C.K., Bergmann, M., Gutow, L., Hanke, G., Van Sebille, E., Angiolillo, M., Buhl-Mortensen, L., Cau, A., Ioakeimidis, C., Kammann, U., Lundsten, L., Papatheodorou, G., Purser, A., Sanchez-Vidal, A., Schulz, M., Vinci, M., Chiba, S., Galgani, F., Langenkämper, D., Möller, T., Nattkemper, T.W., Ruiz, M., Suikkanen, S., Woodall, L., Fakiris, E., Molina Jack, M.E., Giorgetti, A., 2021. The quest for seafloor macrolitter: a critical review of background knowledge, current methods and future prospects. Environmental Research Letters. https://doi.org/10.1088/1748-9326/abc6d4. URL: https://iopscience.iop.org/article/10.1088/1748-9326/abc6d4.

Carlini, G., Kleine, K., 2018. Advancing the international regulation of plastic pollution beyond the United Nations Environment Assembly resolution on marine litter and microplastics. Review of European, Comparative & International Environmental Law 27, 234–244. URL: https://onlinelibrary.wiley.com/doi/10.1111/reel.12258 https://doi.org/10.1111/reel.12258.

Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J.H., Abu-Omar, M., Scott, S.L., Suh, S., 2020. Degradation rates of plastics in the environment. ACS Sustain. Chem. Eng. 8, 3494–3511. URL: https://pubs.acs.org/doi/10.1021/acssuschemeng.9b06635 https://doi.org/10.1021/acssuschemeng.9b06635.

Chenillat, F., Huck, T., Maes, C., Grima, N., Blanke, B., 2021. Fate of floating plastic debris released along the coasts in a global ocean model. Mar. Pollut. Bull. 165, 112116. URL: https://linkinghub.elsevier.com/retrieve/pii/S0025326X21001508 https://doi.org/10.1016/j.marpolbul.2021.112116.

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. URL: https://linkinghub.elsevier.com/retrieve/pii/S0308597X17305195 https://doi.org/10.1016/j.marpol.2018.03.022.

Clarke, A., 2004. Is there a universal temperature dependence of metabolism? Functional Ecology 18, 252–256. URL: http://www.jstor.org/stable/3599365 https://doi.org/10.1111/j.0269-8463.2004.00842.x. publisher: [British Ecological Society, Wiley].

Connan, M., Perold, V., Dilley, B.J., Barbraud, C., Cherel, Y., Ryan, P.G., 2021. The Indian Ocean 'garbage patch': empirical evidence from floating macro-litter. Mar. Pollut. Bull. 169, 112559. URL: https://linkinghub.elsevier.com/retrieve/pii/S0025326X21005932 https://doi.org/10.1016/j.marpolbul.2021.112559.

Corcoran, P.L., Moore, C.J., Jazvac, K., 2014. An anthropogenic marker horizon in the future rock record. GSA Today 4–8. URL: http://www.geosociety.org/gsatoday/archive/24/6/abstract/i1052-5173-24-6-4.htm. doi:(UN, 2023b).

Cózar, A., Sanz-Martín, M., Martí, E., González-Gordillo, J.I., Ubeda, B., Gálvez, José Á. G., Irigoien, X., Duarte, C.M., 2015. Plastic accumulation in the Mediterranean Sea.

PloS One 10, e0121762. URL: https://dx.plos.org/10.1371/journal.pone.0121762 https://doi.org/10.1371/journal.pone.0121762.

Crosti, R., Arcangeli, A., Campana, I., Paraboschi, M., González-Fernández, D., 2018. ‘Down to the river’: amount, composition, and economic sector of litter entering the marine compartment, through the Tiber river in the Western Mediterranean Sea. Rendiconti Lincei. Scienze Fisiche e Naturali 29, 859–866. URL: http://link.springer.com/10.1007/s12210-018-0747-y https://doi.org/10.1007/s12210-018-0747-y.

De Haan, W.P., Sanchez-Vidal, A., Canals, M., 2019. Floating microplastics and aggregate formation in the Western Mediterranean Sea. Mar. Pollut. Bull. 140, 523–535. URL: https://linkinghub.elsevier.com/retrieve/pii/S0025326X19300748 https://doi.org/10.1016/j.marpolbul.2019.01.053.

De Stephanis, R., Giménez, J., Carpinelli, E., Gutierrez-Exposito, C., Cañadas, A., 2013. As main meal for sperm whales: plastics debris. Mar. Pollut. Bull. 69, 206–214. URL: https://linkinghub.elsevier.com/retrieve/pii/S0025326X13000489 https://doi.org/10.1016/j.marpolbul.2013.01.033.

Declerck, A., Delpey, M., Rubio, A., Ferrer, L., Basurko, O.C., Mader, J., Louzao, M., 2019. Transport of floating marine litter in the coastal area of the south-eastern Bay of Biscay: a Lagrangian approach using modelling and observations. Journal of Operational Oceanography 12, S111–S125. URL: https://www.tandfonline.com/doi/full/10.1080/1755876X.2019.1611708 https://doi.org/10.1080/1755876X.2019.1611708.

De-la Torre, G.E., Dioses-Salinas, D.C., Pizarro-Ortega, C.I., Santillán, L., 2021. New plastic formations in the Anthropocene. Sci. Total Environ. 754, 142216. URL: https://linkinghub.elsevier.com/retrieve/pii/S0048969720357454 https://doi.org/10.1016/j.scitotenv.2020.142216.

Deville, A., Vazquez-Rowe, I., Ita-Nagy, D., Kahhat, R., 2023. Ocean-based sources of plastic pollution: an overview of the main marine activities in the Peruvian EEZ. Mar. Pollut. Bull. 189, 114785. URL: https://linkinghub.elsevier.com/retrieve/pii/S0025326X23002163 https://doi.org/10.1016/j.marpolbul.2023.114785.

Dominik, J., Mangini, A., 1979. Late quaternary sedimentation rate variations on the Mediterranean Ridge, as results from the 230Th excess method. Sediment. Geol. 23, 95–112. URL: https://linkinghub.elsevier.com/retrieve/pii/0037073879900083 https://doi.org/10.1016/0037-0738(79)90008-3.

D'Ortenzio, F., Ribera d'Alcalà, M.. On the Trophic Regimes of the Mediterranean Sea: A Satellite Analysis. URL. https://bg.copernicus.org/preprints/5/2959/2008/bgd-5-2959-2008.pdf.

Emig, C., Geistdoerfer, P., . The Mediterranean Deep-sea Fauna: Historical Evolution, Bathymetric Variations and Geographical Changes. URL: https://arxiv.org/abs/q-bio/0507003 https://doi.org/10.48550/ARXIV.Q-BIO/0507003. publisher: arXiv Version Number: 1.

Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., Galgani, F., Ryan, P.G., Reisser, J., 2014. Plastic pollution in the world’s oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PloS One 9, e111913. URL: https://doi.org/10.1371/journal.pone.0111913.

European Commission, 2008. Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 Establishing a Framework for Community Action in the Field of Marine Environmental Policy (Marine Strategy Framework Directive). URL. http://ec.europa.eu/environment/marine/eu-coast-andmarine-policy/marine-strategy-frameworkdirective/index_en.htm.

European Commission, 2018. Proposal for a Directive of the European Parliament and of the Council on Port Reception Facilities for the Delivery of Waste from Ships, Repealing Directive 2000/59/EC and Amending Directive 2009/16/EC and Directive 2010/65/EU. URL. https://ec.europa.eu/info/law/betterregulation/initiatives/com-2018-33_en.

European Union, 2019. Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the Reduction of the Impact of Certain Plastic Products on the Environment. URL: https://eur-lex.europa.eu/eli/dir/2019/904/oj.

Ferentinos, G., Kastanos, N., 1988. Water circulation patterns in the Otranto Straits, eastern Mediterranean. Cont. Shelf Res. 8, 1025–1041. URL: https://linkinghub.elsevier.com/retrieve/pii/0278434388900374 https://doi.org/10.1016/0278-4343(88)90037-4.

Fischer, V., Elsner, N.O., Brenke, N., Schwabe, E., Brandt, A., 2015. Plastic pollution of the Kuril–Kamchatka Trench area (NW pacific). Deep-Sea Res. II Top. Stud. Oceanogr. 111, 399–405. URL: https://linkinghub.elsevier.com/retrieve/pii/S0967064514002173 https://doi.org/10.1016/j.dsr2.2014.08.012.

Fleet, D., Vlachogianni, T., Hanke, G., 2021. Joint list of litter categories for marine macro-litter monitoring: manual for the application of the classification system. In: Technical Report JRC121708. Publications Office, LU. URL: https://data.europa.eu/doi/10.2760/127473.

Fulton, M., Hong, J., Islam, M.J., Sattar, J., 2019. Robotic detection of marine litter using deep visual detection models. In: 2019 International Conference on Robotics and Automation (ICRA). IEEE, Montreal, QC, Canada, pp. 5752–5758. URL: https://ieeexplore.ieee.org/document/8793975/ https://doi.org/10.1109/ICRA.2019.8793975.

Gabitto, J., Tsouris, C., 2008. Drag coefficient and settling velocity for particles of cylindrical shape. Powder Technol. 183, 314–322. URL: https://linkinghub.elsevier.com/retrieve/pii/S0032591007003804 https://doi.org/10.1016/j.powtec.2007.07.031.

Galgani, F., Lecornu, F., 2004. Debris on the seafloor at “Hausgarten”. In: Klages, M., Thiede, J., Foucher, J.P. (Eds.), The expedition ARK XIX/3 of the Research Vessel Polarstern in 2003: Reports of legs 3a, 3b and 3c. Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany, pp. 260–262 number 488 in Reports on Polar and Marine Research.

Galgani, F., Souplet, A., Cadiou, Y., 1996. Accumulation of debris on the deep sea floor off the French Mediterranean coast. Mar. Ecol. Prog. Ser. 142, 225–234. URL: http://www.int-res.com/abstracts/meps/v142/p225-234/ https://doi.org/10.3354/meps142225.

Galgani, F., Leaute, J., Moguedet, P., Souplet, A., Verin, Y., Carpentier, A., Goraguer, H., Latrouite, D., Andral, B., Cadiou, Y., Mahe, J., Poulard, J., Nerisson, P., 2000. Litter on the sea floor along European coasts. Mar. Pollut. Bull. 40, 516–527. URL: https://linkinghub.elsevier.com/retrieve/pii/S0025326X99002349 https://doi.org/10.1016/S0025-326X(99)00234-9.

Galgani, F., Hanke, G., Maes, T., 2015. Global distribution, composition and abundance of marine litter. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, Cham, pp. 29–56. URL: http://link.springer.com/10.1007/978-3-319-16510-3_2 https://doi.org/10.1007/978-3-319-16510-3_2.

Galgani, L., Beiras, R., Galgani, F., Panti, C., Borja, A., 2019. Editorial: impacts of marine litter. Frontiers in Marine Science 6, 208. URL: https://www.frontiersin.org/article/10.3389/fmars.2019.00208/full https://doi.org/10.3389/fmars.2019.00208.

Galgani, F., Lusher, A.L., Strand, J., Haarr, M.L., Vinci, M., Molina Jack, E., Kagi, R., Aliani, S., Herzke, D., Nikiforov, V., Primpke, S., Schmidt, N., Fabres, J., De Witte, B., Solbakken, V.S., Van Bavel, B., 2024. Revisiting the strategy for marine litter monitoring within the european marine strategy framework directive (MSFD). Ocean & Coastal Management 255, 107254. URL: https://linkinghub.elsevier.com/retrieve/pii/S0964569124002394 https://doi.org/10.1016/j.ocecoaman.2024.107254.

Galil, B., Golik, A., Türkay, M., 1995. Litter at the bottom of the sea: a sea bed survey in the eastern Mediterranean. Mar. Pollut. Bull. 30, 22–24. URL: https://linkinghub.elsevier.com/retrieve/pii/0025326X9400103G https://doi.org/10.1016/0025-326X(94)00103-G.

Gewert, B., Plassmann, M.M., MacLeod, M., 2015. Pathways for degradation of plastic polymers floating in the marine environment. Environ. Sci.: Processes Impacts 17, 1513–1521. URL: https://xlink.rsc.org/?DOI=C5EM00207A https://doi.org/10.1039/C5EM00207A.

Hanke, G., Walvoort, D., van Loon, W., Addamo, A.M., Brosich, A., del Mar Chaves Montero, M., Molina Jack, M.E., Vinci, M., Giorgetti, A., 2019. EU marine beach litter baselines: analysis of a pan European 2012 2016 beach litter dataset. In: Technical Report JRC114129. Publications Office, LU. URL: https://data.europa.eu/doi/10.2760/16903.

Hartley, B.L., Pahl, S., Veiga, J., Vlachogianni, T., Vasconcelos, L., Maes, T., Doyle, T., d'Arcy Metcalfe, R., Öztürk, A.A., Di Berardo, M., Thompson, R.C., 2018. Exploring public views on marine litter in Europe: perceived causes, consequences and pathways to change. Mar. Pollut. Bull. 133, 945–955. URL: https://linkinghub.elsevier.com/retrieve/pii/S0025326X18303904 https://doi.org/10.1016/j.marpolbul.2018.05.061.

Haward, M., 2018. Plastic pollution of the world's seas and oceans as a contemporary challenge in ocean governance. Nature Communications 9, 667. URL: https://www.nature.com/articles/s41467-018-03104-3 https://doi.org/10.1038/s41467-018-03104-3.

Hernandez, I., Davies, J.S., Huvenne, V.A.I., Dissanayake, A., 2022. Marine litter in submarine canyons: a systematic review and critical synthesis. Frontiers in Marine Science 9, 965612. URL: https://www.frontiersin.org/articles/10.3389/fmars.2022.965612/full https://doi.org/10.3389/fmars.2022.965612.

Holmström, A., 1975. Plastic films on the bottom of the Skagerack. Nature 255, 622–623. URL: https://www.nature.com/articles/255622a0 https://doi.org/10.1038/255622a0.

Horsman, P.V., 1982. The amount of garbage pollution from merchant ships. Mar. Pollut. Bull. 13, 167–169. URL: https://linkinghub.elsevier.com/retrieve/pii/0025326X82900881 https://doi.org/10.1016/0025-326X(82)90088-1.

Int-Veen, I., Nogueira, P., Isigkeit, J., Hanel, R., Kammann, U., 2021. Positively buoyant but sinking: polymer identification and composition of marine litter at the seafloor of the North Sea and Baltic Sea. Mar. Pollut. Bull. 172, 112876. URL: https://linkinghub.elsevier.com/retrieve/pii/S0025326X21009103 https://doi.org/10.1016/j.marpolbul.2021.112876.

Ioakeimidis, C., Zeri, C., Kaberi, H., Galatchi, M., Antoniadis, K., Streftaris, N., Galgani, F., Papathanassiou, E., Papatheodorou, G., 2014. A comparative study of marine litter on the seafloor of coastal areas in the Eastern Mediterranean and Black Seas. Mar. Pollut. Bull. 89, 296–304. URL: https://linkinghub.elsevier.com/retrieve/pii/S0025326X14006535 https://doi.org/10.1016/j.marpolbul.2014.09.044.

Ioakeimidis, C., Galgani, F., Papatheodorou, G., 2017. Occurrence of marine litter in the marine environment: a world panorama of floating and seafloor plastics. In: Takada, H., Karapanagioti, H.K. (Eds.), Hazardous Chemicals Associated with Plastics in the Marine Environment, 78. Springer International Publishing, Cham, pp. 93–120. URL: https://link.springer.com/10.1007/698_2017_22 https://doi.org/10.1007/698_2017_22 (series Title: The Handbook of Environmental Chemistry).

Jamieson, A.J., Ramsey, J., Lahey, P., 2019. Hadal manned submersible. Sea Technol. 60, 22–24.

Kaandorp, M.L.A., Lobelle, D., Kehl, C., Dijkstra, H.A., Van Sebille, E., 2023. Global mass of buoyant marine plastics dominated by large long-lived debris. Nat. Geosci. 16, 689–694. URL: https://www.nature.com/articles/s41561-023-01216-0 https://doi.org/10.1038/s41561-023-01216-0.

Kaiser, D., Kowalski, N., Waniek, J.J., 2017. Effects of biofouling on the sinking behavior of microplastics. Environ. Res. Lett. 12, 124003. URL: https://iopscience.iop.org/article/10.1088/1748-9326/aa8e8b https://doi.org/10.1088/1748-9326/aa8e8b.

Kiessling, T., Gutow, L., Thiel, M., 2015. Marine litter as habitat and dispersal vector. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, Cham, pp. 141–181. URL: https://doi.org/10.1007/978-3-319-16510-3_6.

Kühn, S., Bravo Rebolledo, E.L., Van Franeker, J.A., 2015. Deleterious effects of litter on marine life. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic

Litter. Springer International Publishing, Cham, pp. 75–116. http://link.springer.com/10.1007/978-3-319-16510-3_4. https://doi.org/10.1007/978-3-319-16510-3_4.

Laist, D.W., 1997. Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. In: Alexander, D.E., Coe, J.M., Rogers, D.B. (Eds.), Marine Debris. Springer New York, New York, NY, pp. 99–139. URL: http://link.springer.com/10.1007/978-1-4613-8486-1_10 https://doi.org/10.1007/978-1-4613-8486-1_10. series Title: Springer Series on Environmental Management.

Laws, E.A., Falkowski, P.G., Smith, W.O., Ducklow, H., McCarthy, J.J., 2000. Temperature effects on export production in the open ocean. Global Biogeochem. Cycles 14, 1231–1246. URL: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/1999GB001229 https://doi.org/10.1029/1999GB001229.

Lebreton, L., 2022. The status and fate of oceanic garbage patches. Nature Reviews Earth & Environment 3, 730–732. URL: https://www.nature.com/articles/s43017-022-00363-z https://doi.org/10.1038/s43017-022-00363-z.

Lebreton, L.C.M., Van Der Zwet, J., Damsteeg, J.W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. Nature Communications 8, 15611. URL: https://www.nature.com/articles/ncomms15611 https://doi.org/10.1038/ncomms15611.

Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., Hajbane, S., Cunsolo, S., Schwarz, A., Levivier, A., Noble, K., Debeljak, P., Maral, H., Schoeneich-Argent, R., Brambini, R., Reisser, J., 2018. Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. Sci. Rep. 8, 4666. URL: https://www.nature.com/articles/s41598-018-22939-w https://doi.org/10.1038/s41598-018-22939-w.

Linley, T.D., Craig, J., Jamieson, A.J., Priede, I.G., 2018. Bathyal and abyssal demersal bait-attending fauna of the Eastern Mediterranean Sea. Mar. Biol. 165, 159. URL: http://link.springer.com/10.1007/s00227-018-3413-0 https://doi.org/10.1007/s00227-018-3413-0.

Lipizer, M., Partescano, E., Rabitti, A., Giorgetti, A., Crise, A., 2014. Qualified temperature, salinity and dissolved oxygen climatologies in a changing Adriatic Sea. Ocean Sci. 10, 771–797. URL: https://os.copernicus.org/articles/10/771/2014/ https://doi.org/10.5194/os-10-771-2014.

Liubartseva, S., Coppini, G., Lecci, R., Clementi, E., 2018. Tracking plastics in the Mediterranean: 2D Lagrangian model. Mar. Pollut. Bull. 129, 151–162. URL: https://linkinghub.elsevier.com/retrieve/pii/S0025326X18301000 https://doi.org/10.1016/j.marpolbul.2018.02.019.

Löhr, A., Savelli, H., Beunen, R., Kalz, M., Ragas, A., Van Belleghem, F., 2017. Solutions for global marine litter pollution. Curr. Opin. Environ. Sustain. 28, 90–99. URL: https://linkinghub.elsevier.com/retrieve/pii/S1877343517300386 https://doi.org/10.1016/j.cosust.2017.08.009.

Maclean, K., Weideman, E.A., Perold, V., Ryan, P.G., 2021. Buoyancy affects stranding rate and dispersal distance of floating litter entering the sea from river mouths. Mar. Pollut. Bull. 173, 113028. URL: https://linkinghub.elsevier.com/retrieve/pii/S0025326X21010626 https://doi.org/10.1016/j.marpolbul.2021.113028.

Madricardo, F., Ghezzo, M., Nesto, N., Mc Kiver, W.J., Faussone, G.C., Fiorin, R., Riccato, F., Mackelworth, P.C., Basta, J., De Pascalis, F., Kruss, A., Petrizzo, A., Moschino, V., 2020. How to deal with seafloor marine litter: an overview of the state-of-the-art and future perspectives. Frontiers in Marine Science 7, 505134. URL: https://www.frontiersin.org/article/10.3389/fmars.2020.505134/full https://doi.org/10.3389/fmars.2020.505134.

Mæland, C.E., Staupe-Delgado, R., 2020. Can the global problem of marine litter be considered a crisis? Risk, Hazards & Crisis in Public Policy 11, 87–104. URL: https://onlinelibrary.wiley.com/doi/10.1002/rhc3.12180 https://doi.org/10.1002/rhc3.12180.

Mankou-Haddadi, N., Bachir-bey, M., Galgani, F., Mokrane, K., Sidi, H., 2021. Benthic marine litter in the coastal zone of Bejaia (Algeria) as indicators of anthropogenic pollution. Mar. Pollut. Bull. 170, 112634. URL: https://linkinghub.elsevier.com/retrieve/pii/S0025326X21006688 https://doi.org/10.1016/j.marpolbul.2021.112634.

Martin, C., Young, C.A., Valluzzi, L., Duarte, C.M., 2022. Ocean sediments as the global sink for marine micro- and mesoplastics. Limnology and Oceanography Letters 7, 235–243. URL: https://aslopubs.onlinelibrary.wiley.com/doi/10.1002/lol2.10257 https://doi.org/10.1002/lol2.10257.

Martins, I., Almeida, C.M.R., Ramos, S., 2021. Plastic pollution in aquatic ecosystems: from research to public awareness. In: Leal Filho, W., Azul, A.M., Brandli, L., Lange Salvia, A., Wall, T. (Eds.), Life Below Water. Springer International Publishing, Cham, pp. 1–12. URL: https://link.springer.com/10.1007/978-3-319-71064-8_141-1 https://doi.org/10.1007/978-3-319-71064-8_141-1. series Title: Encyclopedia of the UN Sustainable Development Goals.

McGlade, J., Samy Fahim, I., Green, D., Landrigan, P., Andrady, A., Costa, M., Geyer, R., Gomes, R., Tan Shau Hwai, A., Jambeck, J., Li, D., Rochman, C., Ryan, P., Thiel, M., Thompson, R., Townsend, K., Turra, A., 2024. From Pollution To Solution: a global assessment of marine litter and plastic pollution. In: Technical Report. URL: https://nottingham-repository.worktribe.com/output/8047115. iSBN: 9789280738810.

Mediterranean Action Plan, 2021. Mediterranean Strategy for the Prevention, Preparedness, and Response to Marine Pollution from Ships (2022–2031). URL. https://www.rempec.org/en/our-work/strategies-and-actions-plans/regional-strategy.

Miyake, H., Shibata, H., Furushima, Y., 2011. Deep-sea litter study using deep-sea observation tools. In: Interdisciplinary Studies on Environmental Chemistry-Marine Environmental Modeling and Analysis. Terrapub, pp. 261–269.

Mordecai, G., Tyler, P.A., Masson, D.G., Huvenne, V.A., 2011. Litter in submarine canyons off the west coast of Portugal. Deep-Sea Res. II Top. Stud. Oceanogr. 58, 2489–2496. URL: https://linkinghub.elsevier.com/retrieve/pii/S0967064511002153 https://doi.org/10.1016/j.dsr2.2011.08.009.

MSFD Technical Group on Marine Litter, 2023. Guidance on the Monitoring of Marine Litter in European Seas: An Update to Improve the Harmonised Monitoring of Marine Litter under the Marine Strategy Framework Directive. Publications Office, LU. URL: https://data.europa.eu/doi/10.2760/59137.

Nakajima, R., Tsuchiya, M., Yabuki, A., Masuda, S., Kitahashi, T., Nagano, Y., Ikuta, T., Isobe, N., Nakata, H., Ritchie, H., Oguri, K., Osafune, S., Kawamura, K., Suzukawa, M., Yamauchi, T., Iijima, K., Yoshida, T., Chiba, S., Fujikura, K., 2021. Massive occurrence of benthic plastic debris at the abyssal seafloor beneath the kuroshio extension, the North West Pacific. Mar. Pollut. Bull. 166, 112188. URL: https://www.sciencedirect.com/science/article/pii/S0025326X21002228 https://doi.org/10.1016/j.marpolbul.2021.112188.

OSPA Commission, 2020. OSPAR scoping study on best practices for the design and recycling of fishing gear as a means to reduce quantities of fishing gear found as marine litter in the North-East Atlantic. In: Technical Report. OSPAR Commission. URL: https://repository.oceanbestpractices.org/handle/11329/1399 10.25607/OBP-905. medium: 128pp.

Ourmieres, Y., Mansui, J., Molcard, A., Galgani, F., Poitou, I., 2018. The boundary current role on the transport and stranding of floating marine litter: the French Riviera case. Cont. Shelf Res. 155, 11–20. URL: https://linkinghub.elsevier.com/retrieve/pii/S0278434317303205 https://doi.org/10.1016/j.csr.2018.01.010.

Pedrosa-Pàmies, R., Parinos, C., Sanchez-Vidal, A., Gogou, A., Calafat, A., Canals, M., Bouloubassi, I., Lampadariou, N., 2015. Composition and sources of sedimentary organic matter in the deep eastern Mediterranean Sea. Biogeosciences 12, 7379–7402. URL: https://bg.copernicus.org/articles/12/7379/2015/ https://doi.org/10.5194/bg-12-7379-2015.

Pedrosa-Pàmies, R., Sanchez-Vidal, A., Canals, M., Lampadariou, N., Velaoras, D., Gogou, A., Parinos, C., Calafat, A., 2016. Enhanced carbon export to the abyssal depths driven by atmosphere dynamics. Geophys. Res. Lett. 43, 8626–8636. URL: https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016GL069781 https://doi.org/10.1002/2016GL069781.

Pedrosa-Pàmies, R., Parinos, C., Sanchez-Vidal, A., Calafat, A., Canals, M., Velaoras, D., Mihalopoulos, N., Kanakidou, M., Lampadariou, N., Gogou, A., 2021. Atmospheric and oceanographic forcing impact particle flux composition and carbon sequestration in the eastern Mediterranean Sea: a three-year time-series study in the deep Ierapetra Basin. Frontiers in Earth Science 9, 591948. URL: https://www.frontiersin.org/articles/10.3389/feart.2021.591948/full https://doi.org/10.3389/feart.2021.591948.

Peng, X., Dasgupta, S., Zhong, G., Du, M., Xu, H., Chen, M., Chen, S., Ta, K., Li, J., 2019. Large debris dumps in the northern South China Sea. Mar. Pollut. Bull. 142, 164–168. URL: https://linkinghub.elsevier.com/retrieve/pii/S0025326X19302255 https://doi.org/10.1016/j.marpolbul.2019.03.041.

Peng, G., Bellerby, R., Zhang, F., Sun, X., Li, D., 2020. The ocean's ultimate trashcan: Hadal trenches as major depositories for plastic pollution. Water Res. 168, 115121. URL: https://linkinghub.elsevier.com/retrieve/pii/S0043135419308954 https://doi.org/10.1016/j.watres.2019.115121.

Pham, C.K., Ramirez-Llodra, E., Alt, C.H.S., Amaro, T., Bergmann, M., Canals, M., Company, J.B., Davies, J., Duineveld, G., Galgani, F., Howell, K.L., Huvenne, V.A.I., Isidro, E., Jones, D.O.B., Lastras, G., Morato, T., Gomes-Pereira, J.N., Purser, A., Stewart, H., Tojeira, I., Tubau, X., Van Rooij, D., Tyler, P.A., 2014. Marine litter distribution and density in European Seas, from the shelves to deep basins. PLoS ONE 9, e95839. URL: https://dx.plos.org/10.1371/journal.pone.0095839 https://doi.org/10.1371/journal.pone.0095839.

Pierdomenico, M., Casalbore, D., Chiocci, F.L., 2019. Massive benthic litter funnelled to deep sea by flash-flood generated hyperpycnal flows. Sci. Rep. 9, 5330. URL: https://www.nature.com/articles/s41598-019-41816-8 https://doi.org/10.1038/s41598-019-41816-8.

Pierdomenico, M., Bernhardt, A., Eggenhuisen, J.T., Clare, M.A., Lo Iacono, C., Casalbore, D., Davies, J.S., Kane, I., Huvenne, V.A., Harris, P.T., 2023. Transport and accumulation of litter in submarine canyons: a geoscience perspective. Frontiers in Marine Science 10, 1224859. URL: https://www.frontiersin.org/articles/10.3389/fmars.2023.1224859/full https://doi.org/10.3389/fmars.2023.1224859.

Politikos, D.V., Ioakeimidis, C., Papatheodorou, G., Tsiaras, K., 2017. Modeling the fate and distribution of floating litter particles in the Aegean Sea (E. Mediterranean). Frontiers in Marine Science 4, 191. URL: http://journal.frontiersin.org/article/10.3389/fmars.2017.00191/full https://doi.org/10.3389/fmars.2017.00191.

Politikos, D., Tsiaras, K., Papatheodorou, G., Anastasopoulou, A., 2020. Modeling of floating marine litter originated from the Eastern Ionian Sea: transport, residence time and connectivity. Mar. Pollut. Bull. 150, 110727. URL: https://linkinghub.elsevier.com/retrieve/pii/S0025326X19308835 https://doi.org/10.1016/j.marpolbul.2019.110727.

Polonia, A., Torelli, L., Mussoni, P., Gasperini, L., Artoni, A., Klaeschen, D., 2011. The Calabrian Arc subduction complex in the Ionian Sea: regional architecture, active deformation, and seismic hazard. Tectonics 30. https://doi.org/10.1029/2010TC002821, 2010TC002821. URL: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2010TC002821.

Polymenakou, P.N., Mandalakis, M., Stephanou, E.G., Tselepides, A., 2008. Particle size distribution of airborne microorganisms and pathogens during an intense African dust event in the eastern Mediterranean. Environ. Health Perspect. 116, 292–296. URL: https://ehp.niehs.nih.gov/doi/10.1289/ehp.10684 https://doi.org/10.1289/ehp.10684.

Prevenios, M., Zeri, C., Tsangaris, C., Liubartseva, S., Fakiris, E., Papatheodorou, G., 2018. Beach litter dynamics on Mediterranean coasts: distinguishing sources and pathways. Mar. Pollut. Bull. 129, 448–457. URL: https://linkinghub.elsevier.com/retrieve/pii/S0025326X17308305 https://doi.org/10.1016/j.marpolbul.2017.10.013.

Price, D.M., Robert, K., Callaway, A., Lo Lacono, C., Hall, R.A., Huvenne, V.A.I., 2019. Using 3D photogrammetry from ROV video to quantify cold-water coral reef structural complexity and investigate its influence on biodiversity and community assemblage. Coral Reefs 38, 1007–1021. URL: http://link.springer.com/10.1007/s00338-019-01827-3 https://doi.org/10.1007/s00338-019-01827-3.

Przeslawski, R., Christenhusz, M.J.M., 2022. Deep-sea discoveries. Zool. J. Linn. Soc. 194, 1037–1043. URL: https://academic.oup.com/zoolinnean/article/194/4/1037/6566246 https://doi.org/10.1093/zoolinnean/zlac022.

Raitsos, D.E., Reid, P.C., Lavender, S.J., Edwards, M., Richardson, A.J., 2005. Extending the SeaWiFS chlorophyll data set back 50 years in the northeast Atlantic. Geophys. Res. Lett. 32. https://doi.org/10.1029/2005GL022484, 2005GL022484. URL: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2005GL022484.

Ramirez-Llodra, E., 2020. Deep-Sea ecosystems: biodiversity and anthropogenic impacts. In: Banet, C. (Ed.), The Law of the Seabed, pp. 36–60. Brill | Nijhoff. URL. https://brill.com/view/book/edcoll/9789004391567/BP000013.xml. https://doi.org/10.1163/9789004391567_004.

Ramirez-Llodra, E., Brandt, A., Danovaro, R., De Mol, B., Escobar, E., German, C.R., Levin, L.A., Martinez Arbizu, P., Menot, L., Buhl-Mortensen, P., Narayanaswamy, B.E., Smith, C.R., Tittensor, D.P., Tyler, P.A., Vanreusel, A., Vecchione, M., 2010. Deep, diverse and definitely different: unique attributes of the world's largest ecosystem. Biogeosciences 7, 2851–2899. URL: https://bg.copernicus.org/articles/7/2851/2010/ https://doi.org/10.5194/bg-7-2851-2010.

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, e22588. URL: https://dx.plos.org/10.1371/journal.pone.0022588 https://doi.org/10.1371/journal.pone.0022588.

Ramirez-Llodra, E., De Mol, B., Company, J.B., Coll, M., Sardà, F., 2013. Effects of natural and anthropogenic processes in the distribution of marine litter in the deep Mediterranean Sea. Prog. Oceanogr. 118, 273–287. URL: https://linkinghub.elsevier.com/retrieve/pii/S0079661113001407 https://doi.org/10.1016/j.pocean.2013.07.027.

Rex, M.A., Etter, R.J., 2010. Deep-Sea Biodiversity: Pattern and Scale. Harvard University Press, USA.

Rochman, C.M., Browne, M.A., Underwood, A.J., van Franeker, J.A., Thompson, R.C., Amaral-Zettler, L.A., 2016. The ecological impacts of marine debris: unraveling the demonstrated evidence from what is perceived. Ecology 97, 302–312. URL: https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1890/14-2070.1 https://doi.org/10.1890/14-2070.1. _eprint: https://esajournals.onlinelibrary.wiley.com/doi/pdf/10.1890/14-2070.1.

Rodríguez-Díaz, L., Gómez-Gesteira, J., Costoya, X., Gómez-Gesteira, M., Gago, J., 2020. The Bay of Biscay as a trapping zone for exogenous plastics of different sizes. J. Sea Res. 163, 101929. URL: https://linkinghub.elsevier.com/retrieve/pii/S1385110120301295 https://doi.org/10.1016/j.seares.2020.101929.

Roether, W., Manca, B.B., Klein, B., Bregant, D., Georgopoulos, D., Beitzel, V., Kovačević, V., Luchetta, A., 1996. Recent changes in eastern Mediterranean deep waters. Science 271, 333–335. URL: https://www.science.org/doi/abs/10.1126/science.271.5247.333 https://doi.org/10.1126/science.271.5247.333. _eprint: https://www.science.org/doi/pdf/10.1126/science.271.5247.333.

Roether, W., Klein, B., Manca, B.B., Theocharis, A., Kioroglou, S., 2007. Transient Eastern Mediterranean deep waters in response to the massive dense-water output of the Aegean Sea in the 1990s. Prog. Oceanogr. 74, 540–571. URL: https://linkinghub.elsevier.com/retrieve/pii/S0079661107000572 https://doi.org/10.1016/j.pocean.2007.03.001.

Ryan, P.G., Perold, V., 2021. Limited dispersal of riverine litter onto nearby beaches during rainfall events. Estuar. Coast. Shelf Sci. 251, 107186. URL: https://linkinghub.elsevier.com/retrieve/pii/S0272771421000226 https://doi.org/10.1016/j.ecss.2021.107186.

Sakellariou, D., Alexandri, M., 2007. Geomorphology of the Hellenic sea-floor. In: State of Hellenic Fisheries. HCMR, Athens, pp. 17–23. Publisher:

Sakellariou, D., Tsampouraki-Kraounaki, K., 2019. Plio-quaternary extension and strike-slip tectonics in the Aegean. In: Transform Plate Boundaries and Fracture Zones. Elsevier, pp. 339–374. URL: https://linkinghub.elsevier.com/retrieve/pii/B9780128120644000141 https://doi.org/10.1016/B978-0-12-812064-4.00014-1.

Sakellariou, D., Drakopoulou, V., Rousakis, G., Livanos, I., Loukaidi, V., Kyriakidou Ch Panagiotopoulos, I., Tsampouraki-Kraounaki, K., Manta, K., 2022. Geomorphological features. In: Otero, M., Mytilineou, C. (Eds.), Deep-Sea Atlas of the Eastern Mediterranean Sea, pp. 20–121.

Santos, F.A., Diório, G.R., Guedes, C.C.F., Fernandino, G., Giannini, P.C., Angulo, R.J., De Souza, M.C., César-Oliveira, M.A.F., Dos Santos Oliveira, A.R., 2022. Plastic debris forms: rock analogues emerging from marine pollution. Mar. Pollut. Bull. 182, 114031. URL: https://linkinghub.elsevier.com/retrieve/pii/S0025326X22007135 https://doi.org/10.1016/j.marpolbul.2022.114031.

Schlining, K., Von Thun, S., Kuhnz, L., Schlining, B., Lundsten, L., Jacobsen Stout, N., Chaney, L., Connor, J., 2013. Debris in the deep: using a 22-year video annotation database to survey marine litter in Monterey Canyon, central California, USA. Deep-Sea Res. I Oceanogr. Res. Pap. 79, 96–105. URL: https://linkinghub.elsevier.com/retrieve/pii/S0967063713001039 https://doi.org/10.1016/j.dsr.2013.05.006.

Seibel, B.A., Drazen, J.C., 2007. The rate of metabolism in marine animals: environmental constraints, ecological demands and energetic opportunities. Philos. Trans. R. Soc., B 362, 2061–2078. URL: https://royalsocietypublishing.org/doi/10.1098/rstb.2007.2101 https://doi.org/10.1098/rstb.2007.2101.

Shimanaga, M., Yanagi, K., 2016. The Ryukyu Trench may function as a “depocenter” for anthropogenic marine litter. J. Oceanogr. 72, 895–903. URL: http://link.springer.com/10.1007/s10872-016-0388-7 https://doi.org/10.1007/s10872-016-0388-7.

Sisma-Ventura, G., Kress, N., Silverman, J., Gertner, Y., Ozer, T., Biton, E., Lazar, A., Gertman, I., Rahav, E., Herut, B., 2021. Post-eastern Mediterranean transient oxygen decline in the deep waters of the Southeast Mediterranean Sea supports weakening of ventilation rates. Frontiers in Marine Science 7, 598686. URL: https://www.frontiersin.org/articles/10.3389/fmars.2020.598686/full https://doi.org/10.3389/fmars.2020.598686.

Smedile, F., Messina, E., La Cono, V., Tsoy, O., Monticelli, L.S., Borghini, M., Giuliano, L., Golyshin, P.N., Mushegian, A., Yakimov, M.M., 2013. Metagenomic analysis of hadopelagic microbial assemblages thriving at the deepest part of Mediterranean Sea, Matapan-Vavilov Deep. Environ. Microbiol. 15, 167–182. URL: https://sfamjournals.onlinelibrary.wiley.com/doi/10.1111/j.1462-2920.2012.02827.x https://doi.org/10.1111/j.1462-2920.2012.02827.x.

Stavrakakis, S., Lykousis, V., 2011. Interannual mass flux variations of settling particles in the NESTOR basins, SE. Ionian Sea (E. Mediterranean), Greece. In: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 626-627, pp. S99–S101. URL: https://linkinghub.elsevier.com/retrieve/pii/S0168900210009307 https://doi.org/10.1016/j.nima.2010.04.076.

Tekman, M.B., Krumpen, T., Bergmann, M., 2017. Marine litter on deep Arctic seafloor continues to increase and spreads to the North at the HAUSGARTEN observatory. Deep-Sea Res. I Oceanogr. Res. Pap. 120, 88–99. URL: https://linkinghub.elsevier.com/retrieve/pii/S096706371630200X https://doi.org/10.1016/j.dsr.2016.12.011.

Thistle, D., 2003. The deep-sea floor: an overview. In: Tyler, P.A. (Ed.), Ecosystems of the World: Ecosystems of the Deep Oceans, volume 28. Elsevier, Amsterdam (The Netherlands), pp. 5–37.

Thompson, R.C., De Falco, F., 2020. Marine litter: are there solutions to this environmental challenge? In: Cocca, M., Di Pace, E., Errico, M.E., Gentile, G., Montarsolo, A., Mossotti, R., Avella, M. (Eds.), Proceedings of the 2nd International Conference on Microplastic Pollution in the Mediterranean Sea. Springer International Publishing, Cham, pp. 39–44. URL: http://link.springer.com/10.1007/978-3-030-45909-3_8 https://doi.org/10.1007/978-3-030-45909-3_8. series Title: Springer Water.

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 304, 838. URL: https://www.science.org/doi/10.1126/science.1094559 https://doi.org/10.1126/science.1094559.

Tubau, X., Canals, M., Lastras, G., Rayo, X., Rivera, J., Amblas, D., 2015. Marine litter on the floor of deep submarine canyons of the Northwestern Mediterranean Sea: the role of hydrodynamic processes. Prog. Oceanogr. 134, 379–403. URL: https://linkinghub.elsevier.com/retrieve/pii/S0079661115000543 https://doi.org/10.1016/j.pocean.2015.03.013.

UN, 2023a. URL: https://www.unep.org/inc-plastic-pollution.

UN, 2023b. URL: https://www.un.org/bbnjagreement/en.

UNEP, 2009. Marine litter: A global challenge. UNEP, Nairobi, Kenya.

UNEP, 2015. Assessment of Marine Litter in the Mediterranean Sea. United Nations Envrionment Programme/Mediterranean Action Plan, Italy.

UNEP, 2021. From Pollution to Solution: A Global Assessment of Marine Litter and Plastic Pollution. UNEP, Nairobi, Kenya.

UNEP, 2024. 2023 Mediterranean Quality Status Report. Technical Report, UNEP.

UNEP/MED, 2021. Regional Plan on Marine Litter Management in the Mediterranean. Technical Report IG.25/27. UNEP/MED. URL: https://www.unep.org/unepmap/meetings/cop-decisions/cop22-outcome-documents.

Van Santvoort, P.J.M., De Lange, G.J., Thomson, J., Colley, S., Meysman, F.J.R., Slomp, C.P., 2002. No title found. Aquat. Geochem. 8, 153–175. URL: http://link.springer.com/10.1023/A:1024271706896 https://doi.org/10.1023/A:1024271706896.

Van Sebille, E., England, M.H., Froyland, G., 2012. Origin, dynamics and evolution of ocean garbage patches from observed surface drifters. Environ. Res. Lett. 7, 044040. URL: https://iopscience.iop.org/article/10.1088/1748-9326/7/4/044040 https://doi.org/10.1088/1748-9326/7/4/044040.

Van Sebille, E., Wilcox, C., Lebreton, L., Maximenko, N., Hardesty, B.D., Van Franeker, J.A., Eriksen, M., Siegel, D., Galgani, F., Law, K.L., 2015. A global inventory of small floating plastic debris. Environ. Res. Lett. 10, 124006. URL: https://iopscience.iop.org/article/10.1088/1748-9326/10/12/124006 2020031315134210.

Wei, C.L., Rowe, G.T., Nunnally, C.C., Wicksten, M.K., 2012. Anthropogenic “litter” and macrophyte detritus in the deep Northern Gulf of Mexico. Mar. Pollut. Bull. 64, 966–973. URL: https://linkinghub.elsevier.com/retrieve/pii/S0025326X12000938 https://doi.org/10.1016/j.marpolbul.2012.02.015.

Weiss, Ludwig, Heussner, Canals, Ghiglione, Estournel, Constant and Kerhervà Weiss, L., Ludwig, W., Heussner, S., Canals, M., Ghiglione, J.F., Estournel, C., Constant, M., Kerhervé, P., 2021. The missing ocean plastic sink: gone with the rivers. Science 373, 107–111. URL: https://www.science.org/doi/10.1126/science.abe0290 https://doi.org/10.1126/science.abe0290.

Werner, S., Budziak, A., van Franeker, J.A., Galgani, F., Hanke, G., Maes, T., Mattidi, M., Nilsson, P., Oosterbaan, L., Priestland, E., Thompson, R., Veiga, J., Vlachogianni, T., 2016. Harm caused by marine litter: MSFD GES TG marine litter: thematic report. In: Technical Report JRC104308. Publications Office, LU. URL: https://data.europa.eu/doi/10.2788/690366.

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. Royal Society Open Science 1, 140317. URL: https://royalsocietypublishing.org/doi/10.1098/rsos.140317 https://doi.org/10.1098/rsos.140317.

Woodall, L.C., Robinson, L.F., Rogers, A.D., Narayanaswamy, B.E., Paterson, G.L.J., 2015. Deep-sea litter: a comparison of seamounts, banks and a ridge in the Atlantic and Indian Oceans reveals both environmental and anthropogenic factors impact accumulation and composition. Frontiers in Marine Science 2. https://doi.org/10.3389/fmars.2015.00003. URL: http://journal.frontiersin.org/Article/10.3389/fmars.2015.00003/abstract.

Young, J., 2020. Expedition Deep Ocean: The First Descent to the Bottom of All Five of the World's Oceans. Simon and Schuster, New York, US.

Zambianchi, E., Iermano, I., Suaria, G., Aliani, S., et al., 2014. Marine litter in the Mediterranean Sea: an oceanographic perspective. In: Marine Litter in the Mediterranean and Black Seas Ciesm Workshop Monograph. CIESM Publisher, pp. 31–41.

Zhu, X., Rochman, C.M., Hardesty, B.D., Wilcox, C., 2024. Plastics in the deep sea – a global estimate of the ocean floor reservoir. Deep-Sea Res. I Oceanogr. Res. Pap. 206, 104266. URL: https://linkinghub.elsevier.com/retrieve/pii/S0967063724000360 https://doi.org/10.1016/j.dsr.2024.104266.