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First assessment of anthropogenic impacts in submarine canyon systems off southwestern Australia

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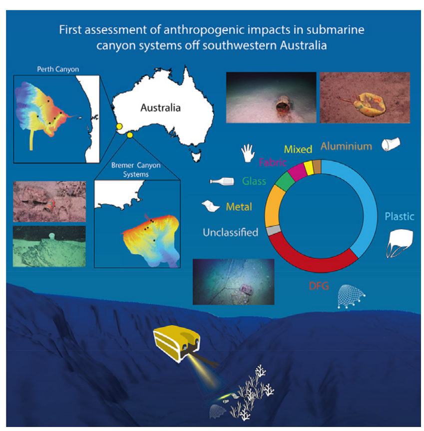
HIGHLIGHTS

- First ROV exploration of macro-litter in submarine canyons of southwest Australia
- These canyons are much less impacted compared to most of those studied worldwide.
- Canyon megabenthos (including deep water corals) is not yet affected by macro-litter.
- We set a baseline for monitoring the status of habitats and littering.

GRAPHICAL ABSTRACT



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ABSTRACT

We assessed the anthropogenic impacts on southwestern Australian submarine canyons by quantifying macro-litter discovered during Remotely Operated Vehicle surveys. The study area encompasses the Bremer canyon systems and Perth Canyon. The categories of macro-litter identified by our study are plastic, metal, aluminium, glass, fabric, mixed, derelict fishing gear, and unclassified. The anthropogenic impacts in the canyons explored is minimal, especially in the Bremer canyon systems, whereas Perth Canyon has comparatively more macro-litter, presumably due to intense maritime traffic and nearby urban development. On a global scale, however, the environmental status of southwestern Australian canyons is relatively pristine. This analysis provides a baseline for the monitoring and enduring stewardship of these habitats where lush and diverse biota, including deep-sea corals, thrive.

1. Introduction

Marine litter is recognized as a global menace to the health of the oceans, from shorelines to the deep seabed (Bergmann et al., 2015; Botero et al., 2020; Ceccarelli, 2009; Chiba et al., 2018; Consoli et al., 2018a; Derraik, 2002; Galgani et al., 2000; Galgani, 2015; Galgani et al., 2015; Harris et al., 2021;

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Ioakeimidis et al., 2015; Jeftic et al., 2009; Pham et al., 2014; Pierdomenico et al., 2019; Spedicato et al., 2019; Tekman et al., 2022; Woodall et al., 2015). Litter poses a threat to marine benthic organisms in different ways: alterating food webs (Peng et al., 2020), the indirect catch of fish species (ghost fishing), direct physical impact on habitats or species by entanglement that may cause damage by pulling, breaking, covering sessile organisms and obstructing suspension feeders (Consoli et al., 2018b; Angiolillo et al., 2021).

Submarine canyons are known hotspots of biodiversity (De Leo et al., 2010; Robertson et al., 2020); for instance, charismatic and vulnerable cold (deep)-water corals commonly inhabit canyon settings where they might be exposed to anthropogenic impacts (Amaro et al., 2016; Angiolillo et al., 2021; Appah et al., 2022; D'Onghia et al., 2016; Fabri et al., 2014; Giusti et al., 2019; Lastras et al., 2016; Orejas et al., 2009; Pohl et al., 2020; Schlining et al., 2013; Taviani et al., 2017; Tubau et al., 2015). The condition of submarine canyons ranges from almost intact to highly degraded, at times strongly impacted by a number of stressors such as littering and fishing (Cau et al., 2017; Fernandez-Arcaya et al., 2017; Galgani et al., 1996; Mordecai et al., 2011; Ramirez-Llodra et al., 2011; Silva and Araújo, 2021; D'Onghia et al., 2017; van den Beld et al., 2017).

Since submarine canyons also provide fundamental ecosystem services and goods (De Leo et al., 2010; Fernandez-Arcaya et al., 2017), their health needs to be safeguarded by implementing suitable governance programs to sustain the Blue Economy, conforming to the United Nations Decade of Ocean Science for Sustainable Development (UNESCO, 2021; Silva and Araújo, 2021). One major step to achieve this goal is to better constrain the distribution, typology, and impacts of seafloor marine macro-litter in the World's oceans, a crucial prerequisite to foster adequate societal responses (Canals et al., 2021; Silva and Araújo, 2021). However, only a small fraction of submarine canyons have been assessed thus far in terms of anthropogenic footprint, which underscores the urgent need to fill such gaps in our limited knowledge of the deep ocean (Fig. 1).

In relation to such anthropogenic impacts, virtually no information is available for the deep seabed of southwestern Australia (see https://www.awe.gov.au/environment/marine/marine-pollution/marine-debris), due to the lack of deep-sea remotely operated vehicle (ROV) exploration of these environments. We present here the first quantitative assessment of macro-litter (items >25 mm in the longest dimension: Fleet et al., 2021) found in several large submarine canyon systems along the SW Australian

Fig. 1. Global distribution of studies in the literature reporting and/or quantifying litter in submarine canyons. 1: Quattrini et al., 2015; 2: Cleland et al., 2021; 3–4: Schlining et al., 2013, Watters et al., 2010; 5: Wei et al., 2012; 6–7: Buhl-Mortensen and Buhl-Mortensen, 2017, 2018; 8: Appah et al., 2022; 9: Pham et al., 2014; 10–13: Dominguez-Carrió et al., 2020, Fabri et al., 2019, Gerigny et al., 2019, Lastras et al., 2016; 14: Gerigny et al., 2019; 15–16: Ramirez-Llodra et al., 2013, Mecho et al., 2018; 17–18: Giusti et al., 2019, Enrichetti et al., 2020; 19: Grinyó et al., 2021; 20–22: Taviani et al., 2017; Cau et al., 2017, Moccia et al., 2019; 23: Taviani et al., 2019; 24: Angeletti et al., 2014; 25: Chimienti et al., 2020; 26: Prampolini et al., 2020; 27–28: Pierdomenico et al. 2019–2020; 29: Oliveira et al., 2015; 30: Mecho et al., 2020; 31: Zhong and Peng, 2021; 32: Trotter et al., 2019; 33: Galgani and Lecomu, 2004.

continental margin, based upon recently acquired images by deep-sea ROV (Trotter et al., 2019, 2021, 2022). The canyons explored incise the southwestern Indian and Southern Ocean sectors of Australia's passive margin, and have no present connection to any recent fluvial system (Heap and Harris, 2008; Harris and Whiteway, 2011). Such features differ from many submarine canyons around the world (McCulloch et al., 2017; Trotter et al., 2019, 2021, 2022), where fluvial connection can be major conduits for land generated anthropogenic litter. Our study sites are within the Bremer Marine Park (Trotter et al., 2022) and the Perth Canyon Marine Park (McCulloch et al., 2017; Trotter et al., 2019, 2021, 2022) located in the Australian Southern Ocean and adjacent southeast Indian Ocean.

Our observations are limited to macro-litter on the seabed, whereas assessing globally-pervasive microplastics (Andrady, 2011; Bergmann et al., 2018; Peng et al., 2020; Reisser et al., 2013; Woodall et al., 2015) requires specialized sampling techniques that were incompatible with our main research goals and is thus beyond the scope of this study. Quantifying these observations is also a pre-requisite for evaluating the environmental status of the resident biota and to implement appropriate measures for future long-term maintenance (e.g., Danovaro et al., 2020; Kazanidis et al., 2020; Galgani et al., 2022).

1.1. Study area

1.1.1. Oceanographic setting

The southern boundary of Australia is characterized by complex oceanographic dynamics that sustain periodic upwelling phenomena, assisted by the presence of several submarine canyons that incise the continental shelf and slopes. In the shallowest layer of the water column to ~300 m depth, the Leeuwin Current transports warmer and more saline South Indian Central Water (SICW, Cresswell and Peterson, 1993) southwards from the equatorial North-West Shelf region, then eastwards to Tasmania (Wijeratne et al., 2018; Akhir et al., 2020). Beneath the Leeuwin Current, the Flinders Current flows westward from Tasmania to Cape Leeuwin then northwards (as the Leeuwin Undercurrent) to the Perth Canyon, transporting highly oxygenated Subantarctic Mode Water (SAMW) formed by deep winter convection in the region south of Australia (McCartney, 1977; Wong, 2005; Woo and Pattiaratchi, 2008). The Flinders Current flows within a depth range of ~300 to ~750 m reaching a maximum depth of 800–1000 m (Middleton and Bye, 2007; Duran et al., 2020). Below the SAMW between ~800–1300 m is the Antarctic Intermediate Water (AAIW) that originates in the Antarctic Polar Zone (Molinelli, 1981; Fine, 1993; Sloyan and Rintoul, 2001). Underlying the AAIW, the Upper Circumpolar Deep Water (UCDW) flows at depths of ~1500 to ~2600 m, whilst the Lower Circumpolar Deep Water (LCDW) comprises the deepest water mass which ranges between 2600 and 3500 m.

1.1.2. Geomorphological setting

1.1.2.1. The Bremer canyon systems (BCS). Seven submarine canyons deeply incise the portion of the continental margin of the Bremer Sub-Basin from the uppermost slope to the base of the scarp (Fig. 1). In the easternmost part of the BCS area, the Bremer Canyon is composed of five main branches extending from the shelf break at 140–380 m to >2000 m. The head of the canyon reaches slope angles of 60°, which become flatter and more U-shaped around 2200 m when it merges with the Bremer Channel. The adjacent Hood Canyon, the head of which is located at ~500–600 m depth, has slopes ranging from 10° to 65° that gradually diminish seawards. The head encompasses multiple tributaries that connect to a single channel, about 2500 m deep and about 5 km wide. To the southwest, the Henry and Knob canyons incise the continental slope from 650 to 900 m down to 3400 and 3600 m where they merge with the wide Bremer Channel. A tributary of the Knob Canyon almost reaches the shelf break at ~180 m. The gradient of the canyons heads is about 40°. The seabed of the canyons' is generally of coarse–grained or mixed sediments and muddy along the flanks with rocks outcropping within gullies and scarps.

1.1.2.2. Perth Canyon. The Perth Canyon is a blind canyon that extends from the continental slope to the abyssal plain (to about 4000 m depth) covering an area of >1500 km^2. The canyon is defined by two V-shaped sinuous tributaries and steep walls with angles from 30° to 40°, which increase in the deepest sector reaching ~70°. Around the Perth Canyon there are numerous smaller blind canyons along the continental slope from 1700 m to 3900 m water depth. These canyons run *E*-W and straight down to the Perth abyssal plain, parallel to the deepest arm of the Perth Canyon (McCulloch et al., 2017; Trotter et al., 2019).

2. Materials and methods

Cruise FK200126 was undertaken during the austral summer from January 26th to February 26th aboard the RV *Falkor* provided by the not-for-profit Schmidt Ocean Institute (SOI). *Falkor*'s multibeam sonar system was used for bathymetric mapping. The SOI's custom-built remotely operated vehicle, *SuBastian*, was deployed to collect in-situ some representative fauna (especially deep-water corals), sediments, seawater, and rocks from the canyons and shelf environments, as well as to record images of these largely unexplored habitats including macro-litter on the substrate.

2.1. Multibeam bathymetric analysis

High-resolution bathymetric data were acquired using both Kongsberg EM 302 and 710 multibeam echo sounders. The multibeam echo-sounder data was processed onboard using Quimera software generating dynamic surface using the cube option at variable resolution, 10 m from 200 m to 1500 water depths and 30 m for greater water depths. The data were 'cleaned' using the Swath Editor that consists of interactively selecting and rejecting soundings as well as filtering functions, which automatically detected and rejected outliers. Digital terrain models (DTMs) were generated for each survey area at variable resolution depending on the water depth. The DTMs were exported in ASCII ESRI format and analyzed with ArcGIS 10.5. Using the ArcGIS Spatial Analyst tool, we derived the hill shade from the DTM with a vertical exaggeration of 1.5.

2.2. Benthic marine macro-litter detection and classification

Images from all ROV transects were primarily annotated in real-time during the dives using *Falkor*'s video annotation software, SQUIDLE+, with some edits made post-survey (http://squidle.org/). SQUIDLE+ is a new improved online and in-field platform for the management and annotation of Georeferenced images and videos. We customized the classification list to include anthropogenic impacts, to which we assigned in real-time all litter observed during the dives. For each dive we exported an .xls file storing both annotations, image name, date, time, and coordinates for each image recorded every 5 s. The litter items were counted and density (item km^{-1}) was calculated as the ratio between items and dive lengths, considering the entire set of dives performed in each area. We transformed the .xls files in point shapefile (.shp) to be further analyzed in GIS software (ArcMap10.8). We selected from the .shp files all points labeled as anthropogenic to be plotted on the Multi Beam DTM. Post-cruise, still images labeled with 'anthropogenic' were visually analyzed and all benthic litter items further classified as: glass, fabric, plastic metal, derelict fishing gear (DFG), mixed, or unclassified (Fig. 2). A map was then compiled showing all classified benthic marine litter items observed in the areas surveyed.

2.3. Literature data

A systematic and bibliometric literature review was performed using a quantitative approach to identify and analyze existing studies that report the presence of seafloor litter specifically in submarine canyon systems. The search was limited to records providing macro-litter occurrences, hence excluding those focusing on micro-litter (e.g., microplastics). Two databases, Scopus (scopus.com) and the Web of Science (webofknowledge.com), were used employing the query terms "litter"

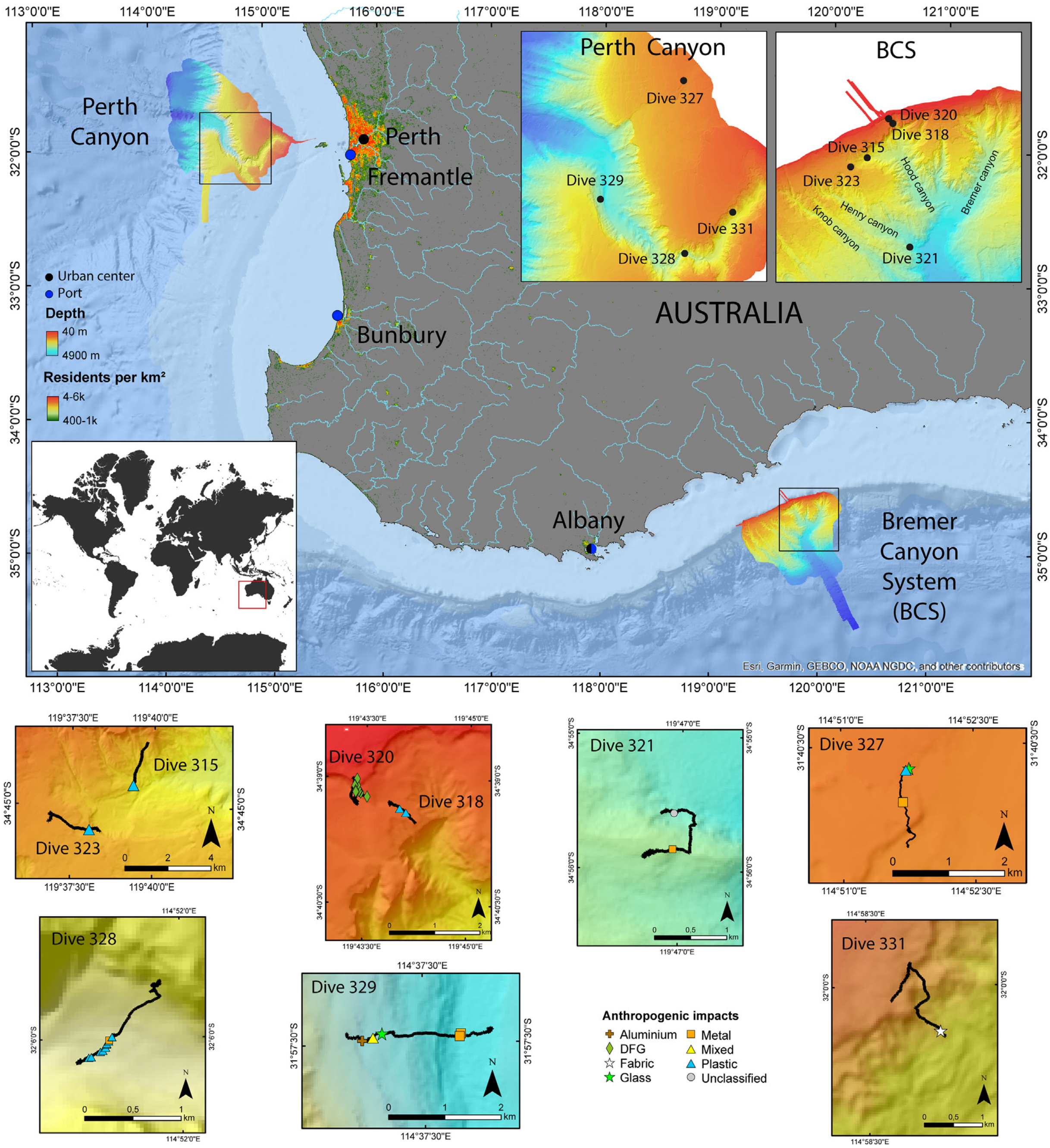

Fig. 2. Location of dives reporting occurrence of macro-litter in the Perth Canyon and Bremer canyon systems and the distribution of macro-litter categories along the dives paths. The location of the complete Dive list can be found at https://soi.squidle.org/geodata/explore?filters=%7B%22platform_ids%22:[10]%7D#map. Major urban centers with the population density (source: https://ghsl.jrc.ec.europa.eu), ports (source: https://msi.nga.mil/) and water courses are showed.

AND "canyon". A cross-check between the results from these two databases was performed to exclude duplicate records. The locations of studies fulfilling the criteria were then extracted and converted into spatial data using ArcGIS 10.5 software (© ESRI).

3. Results

Marine macro-litter was identified, categorized, and mapped during the FK200126 mission, documenting direct evidence of human imprints on the deep-sea bottom off SW Australia. The typology of marine litter recorded during our ROV dives includes some of the most common types of marine debris listed by Butterworth et al., 2012, i.e., bags, glass bottles, cans, and ropes, as well as abandoned or derelict fishing gear. A total of 28 items were documented in the areas explored within the Bremer canyon systems and Perth Canyon Marine Park.

3.1. Bremer canyon systems

Ten ROV dives (312 to 323) were undertaken within the Bremer Marine Park, in and around the Bremer and Hood canyons in particular, and near the mouth of the Henry and Knob canyons (Fig. 2). The dives explored a wide area and depth range, from sites near the mouth of the canyon systems (312,321) to the shallower depths of the continental shelf (318, 320), but mostly the intermediate depths along the northern flanks and walls of the canyons (313, 314, 315, 322, 323). The surveys explored the substrate from ~180 to 3300 m depths.

Table 1
Table reporting the benthic macro-litter items identified in the explored sites with categories, quantity, depth of occurrence and length of the dive.

Area	DIVE	Latitude (ddeg)	Longitude (ddeg)	Item	Category	Item	Depth (m)	Length (m)
BCS	Dive 315	−34.74	119.66	Plastic bag	Plastic	1	1531.32	2791.37
BCS	Dive 318	−34.66	119.73	Plastic ball	Plastic	1	489.24	1181.83
BCS	Dive 318	−34.66	119.73	Nylon Net	Plastic	1	459.10	2702.95
BCS	Dive 320	−34.65	119.73	Longline	DFG	1	328.48	2702.95
BCS	Dive 320	−34.65	119.72	Longline	DFG	1	328.06	2702.95
BCS	Dive 320	−34.65	119.72	Longline	DFG	1	305.69	2702.95
BCS	Dive 320	−34.65	119.72	Longline	DFG	1	303.94	2702.95
BCS	Dive 320	−34.65	119.72	Longline	DFG	1	280.70	2702.95
BCS	Dive 320	−34.65	119.72	Longline	DFG	1	233.17	2702.95
BCS	Dive 320	−34.65	119.72	Longline	DFG	1	185.18	2702.95
BCS	Dive 320	−34.65	119.72	Longline	DFG	1	265.57	2702.95
BCS	Dive 320	−34.65	119.72	Cage and Longline	DFG	1	267.10	2702.95
BCS	Dive 320	−34.65	119.72	Longline	DFG	1	270.05	2702.95
BCS	Dive 320	−34.65	119.72	Longline	DFG	1	337.31	2702.95
BCS	Dive 320	−34.65	119.72	Longline	DFG	1	357.56	2702.95
BCS	Dive 321	−34.93	119.78	Unknown	Unclassified	1	2953.41	2922.79
BCS	Dive 321	−34.93	119.78	Barrel	Metal	1	2591.99	2922.79
BCS	Dive 323	−34.76	119.63	Plastic pipe	Plastic	1	1118.51	5842.12
Perth Canyon	Dive 327	−31.68	114.86	Can	Metal	1	671.59	2913.50
Perth Canyon	Dive 327	−31.68	114.86	Glass bottle	Glass	1	678.99	2913.50
Perth Canyon	Dive 327	−31.68	114.86	Metal Strip	Metal	1	673.86	2913.50
Perth Canyon	Dive 328	−32.10	114.86	Plastic bag	Plastic	1	2256.11	2613.92
Perth Canyon	Dive 328	−32.10	114.86	Plastic bag	Plastic	1	2257.29	2613.92
Perth Canyon	Dive 328	−32.10	114.86	Plastic bag	Plastic	1	2258.87	2613.92
Perth Canyon	Dive 328	−32.10	114.86	Plastic bag	Plastic	2	2257.62	2613.92
Perth Canyon	Dive 328	−32.10	114.86	Plastic cup	Plastic	1	2251.21	2613.92
Perth Canyon	Dive 328	−32.10	114.86	Plastic strap	Plastic	1	2247.61	2613.92
Perth Canyon	Dive 328	−32.10	114.86	Plastic cladding	Plastic	1	2244.01	2613.92
Perth Canyon	Dive 328	−32.10	114.86	Plastic bag	Plastic	1	2241.35	2613.92
Perth Canyon	Dive 328	−32.10	114.86	Metal component	Metal	1	2240.57	2613.92
Perth Canyon	Dive 328	−32.10	114.86	Plastic bag	Plastic	1	2240.84	2613.92
Perth Canyon	Dive 329	−31.96	114.63	Metal lid	Metal	1	2998.71	4282.91
Perth Canyon	Dive 329	−31.96	114.63	Metal barrel	Metal	1	3002.14	4282.91
Perth Canyon	Dive 329	−31.96	114.62	Glass Bottle	Glass	1	2657.01	4282.91
Perth Canyon	Dive 329	−31.96	114.62	Glove	Fabric	1	2652.26	4282.91
Perth Canyon	Dive 329	−31.96	114.62	Ordnance	Mixed	1	2632.93	4282.91
Perth Canyon	Dive 329	−31.96	114.61	Can	Aluminum	1	2602.75	4282.91
Perth Canyon	Dive 331	−32.01	114.99	Canvas	Fabric	1	1082.90	2710.75

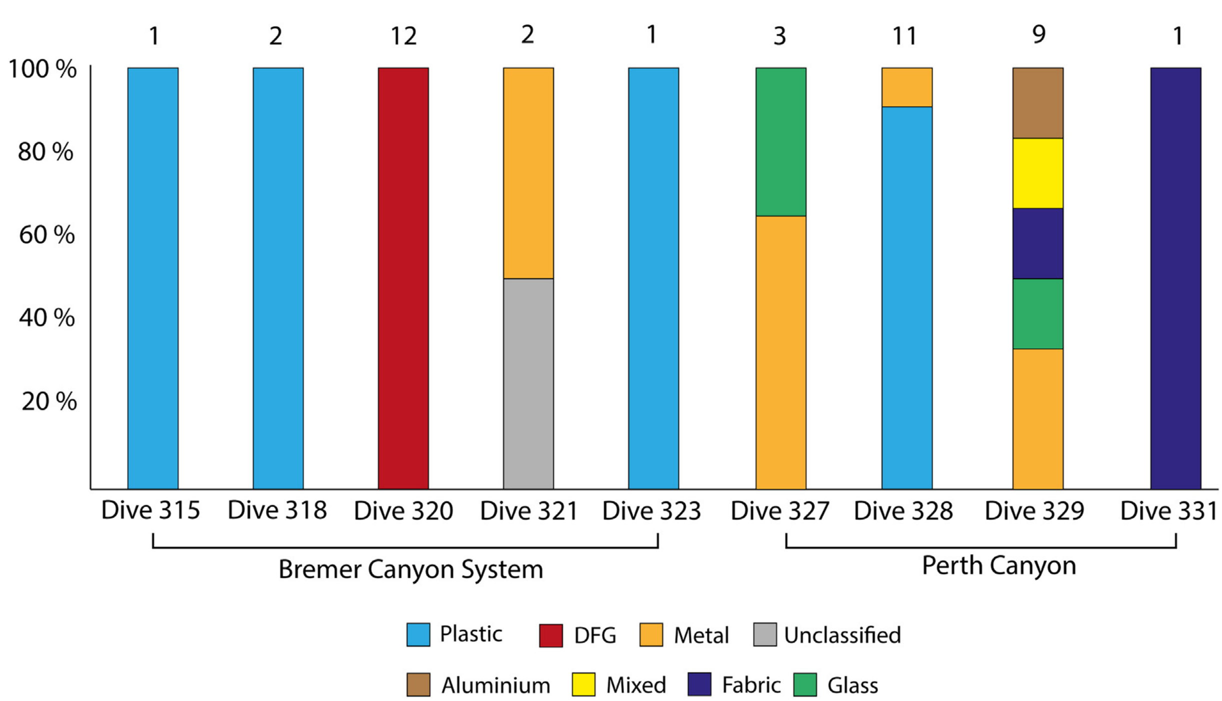

Fig. 3. Percent contribution of litter categories in areas explored in the BCS. The total number of macro-litter items is reported. The category "unknown" was used when litter was not identifiable. DFG: derelict fishing gear.

A small amount of macro-litter was observed during five dives (315, 318, 320, 321, 323), which mainly consisted of plastic and metal items, and derelict fishing gear (Fig. 2). Dives 315, 318, 320 and 323 surveyed different portions of the head of the Hood Canyon within a depth range of 180–1550 m. The lowest density of benthic macro-litter was documented in Dive 315 (0.36 items km^{-1}), with only one plastic item detected in >2700 m of seafloor explored (Table 1, Figs. 3–4). Two plastic items were identified in 1182 m of seafloor surveyed during Dive 318, resulting in macro-litter density of 1.69 items km^{-1}. Dive 320 explored the shallowest section of the Hood Canyon (~180–390 m), where various types of derelict fishing gear were documented along the 2700 m transect, mostly represented by longlines entangling rocky outcrops emerging from the seafloor. Here, the highest litter density was registered, reaching 4.44 items km^{-1}. In the westernmost part of the Hood Canyon explored, Dive 323 represents the longest dive traverse that extended >5800 m. The presence of macro-litter was minimal, with only one plastic item observed (= 0.17 items km^{-1}).

The southernmost survey that yielded macro-litter, Dive 321, transited ~4200 m of muddy floor and rocky flanks near the mouth of the Henry Canyon, between ~900 and ~1300 m water depths. The seafloor was mostly devoid of macro-litter (0.47 items km^{-1}) except for a metal item (barrel) observed on the soft substrate and an unidentified item.

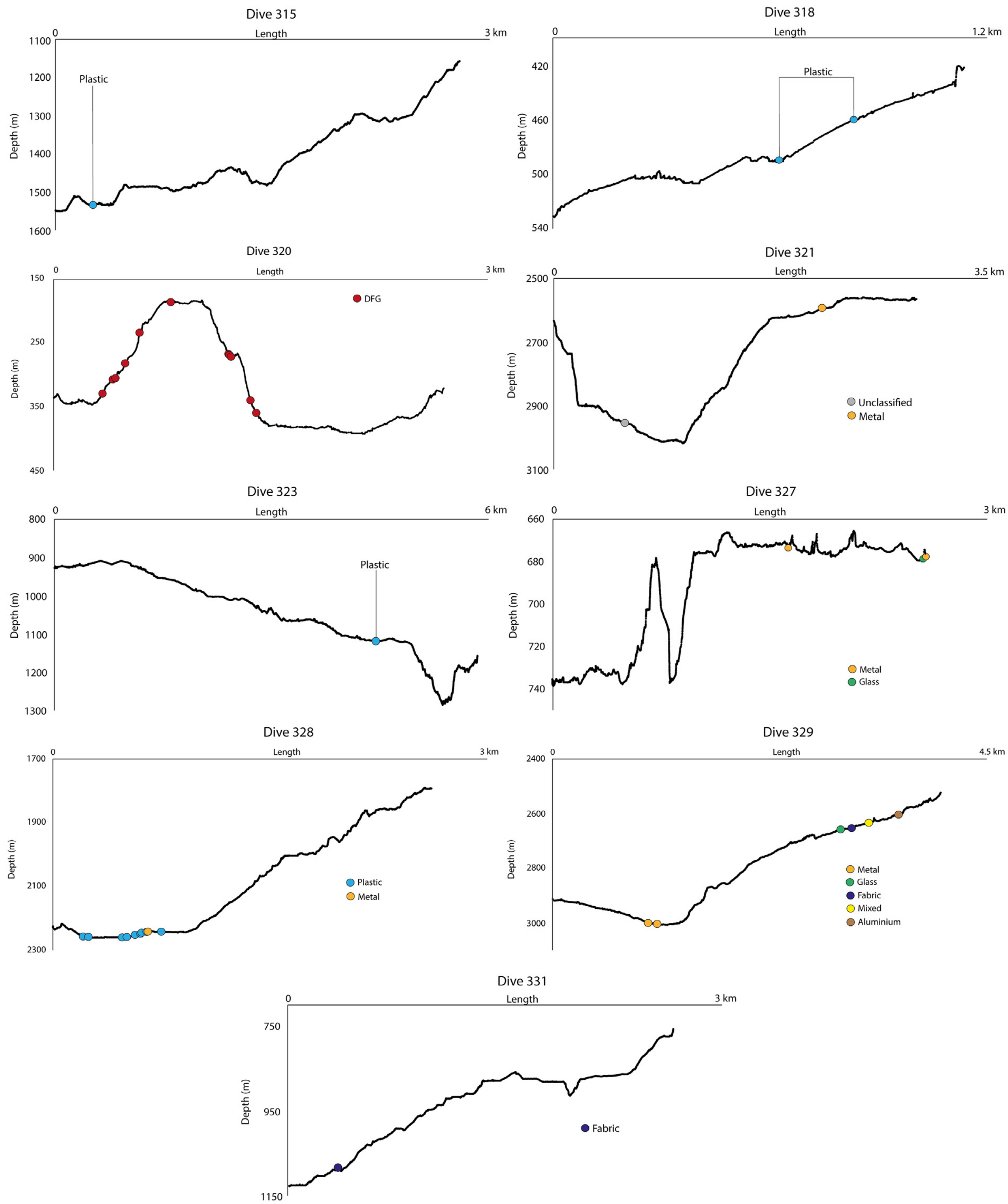

Fig. 4. Bathymetric profile and the occurrence of litter items, divided by categories, identified along the dives tracks.

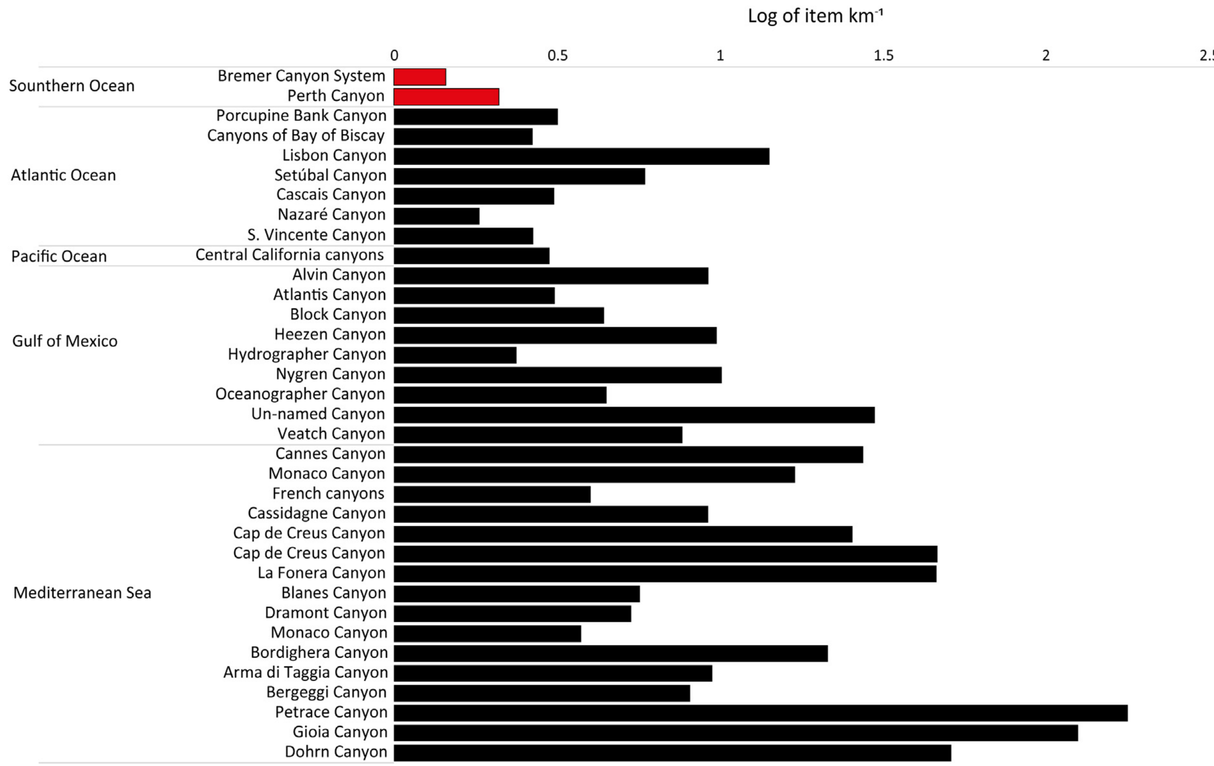

Fig. 5. Bar plot showing the presence of litter, quantity expressed as log(n + 1) of item km^{-1}, in submarine canyons at global scale. References are reported in Table 1.

Table 2
Comparison of litter densities on the seafloor from the literature and this study by considering both litter and fishing-related waste (GW, general waste) and by dividing litter from derelict fishing gear (DFG) and fishing impacts.

Area	Location	Depth (m)	GW item km^{-1}	Litter item km^{-1}	DFG item km^{-1}	Ref
BCS	Southern Ocean	180–3020	1.08	0.36	0.72	This study
Perth Canyon	Southern Ocean	740–3000	1.71	1.71	0	This study
Porcupine Bank Canyon	Atlantic Ocean	567–2126	2.15	–	–	Appah et al., 2022
Canyons of Bay of Biscay	Atlantic Ocean	223–2359	1.66	–	–	van den Beld et al., 2017
Lisbon	Atlantic Ocean	1602	13.2	–	–	Mordecai et al., 2011
Setúbal	Atlantic Ocean	2194	4.9	–	–	Mordecai et al., 2011
Cascais	Atlantic Ocean	4574	2.1	–	–	Mordecai et al., 2011
Nazaré	Atlantic Ocean	741–4385	0.83	–	–	Mordecai et al., 2011
S. Vincente Canyon	Atlantic Ocean	93–553	1.67	–	–	Oliveira et al., 2015
Central California canyons	Pacific Ocean	20–365	1.8–3.2	–	–	Watters et al., 2010
Alvin Canyon	Gulf of Mexico	846–1110	8.22	–	–	Quattrini et al., 2015
Atlantis Canyon	Gulf of Mexico	885–1794	2.11	–	–	Quattrini et al., 2015
Block Canyon	Gulf of Mexico	1044–2135	3.41	–	–	Quattrini et al., 2015
Heezen Canyon	Gulf of Mexico	703–1723	8.78	–	–	Quattrini et al., 2015
Hydrographer Canyon	Gulf of Mexico	580–1423	1.38	–	–	Quattrini et al., 2015
Nygren Canyon	Gulf of Mexico	678–1590	9.14	–	–	Quattrini et al., 2015
Oceanographer Canyon	Gulf of Mexico	983–1248	3.49	–	–	Quattrini et al., 2015
Un-named Canyon	Gulf of Mexico	1018–1139	28.89	–	–	Quattrini et al., 2015
Veatch Canyon	Gulf of Mexico	1967–2026	6.67	–	–	Quattrini et al., 2015
Cannes Canyon	Mediterranean Sea	945–1443	26.5	25.6	0.9	Angiolillo et al., 2021
Monaco Canyon	Mediterranean Sea	1291–2194	16	15.4	0.6	Angiolillo et al., 2021
French canyons	Mediterranean Sea	80–700	3.01	–	–	Fabri et al., 2014
Cassidagne Canyon	Mediterranean Sea	200–515	8.2			Fabri et al., 2019
Cap de Creus Canyon	Mediterranean Sea	156–1570	24.53	–	–	Tubau et al., 2015
Cap de Creus Canyon	Mediterranean Sea	150–400	45.5			Dominguez-Carrió et al., 2020
La Fonera Canyon	Mediterranean Sea	140–1731	45.17	–	–	Tubau et al., 2015
Blanes Canyon	Mediterranean Sea	165–1492	4.68	–	–	Tubau et al., 2015
Dramont	Mediterranean Sea	20–342	4.34	–	–	Giusti et al., 2019
Monaco	Mediterranean Sea	40–251	2.75	–	–	Giusti et al., 2019
Bordighera	Mediterranean Sea	20–300	20.46	–	–	Giusti et al., 2019
Arma di Taggia	Mediterranean Sea	25–95	8.47	–	–	Giusti et al., 2019
Bergeggi	Mediterranean Sea	230–445	7.10	–	–	Giusti et al., 2019
Petrace Canyon	Mediterranean Sea	40–260	177.43	–	–	Pierdomenico et al., 2020
Gioia Canyon	Mediterranean Sea	17–541	124.71	–	–	Pierdomenico et al., 2020
Dohrn Canyon	Mediterranean Sea	140–634	50.3		15.9	Taviani et al., 2019

3.2. Perth Canyon

Five ROV dives (327 to 331) were undertaken in the Perth Canyon, four of which were impacted by macro-litter (327, 328, 329, 331) (Fig. 2). The dives targeted sites from the shallower continental shelf to the deeper reaches of the canyon to ~3000 m depth. The seabed was observed to be more impacted by anthropogenic items than the sites surveyed in the Bremer canyon systems. Our survey identified four main types of macro-litter: plastics (e.g., bags, cups), glass (bottles), metal (cans), fabric (clothes) and mixed (ordnance; Table 1). Plastic objects represent the most common human-derived material. Larger items include inert military objects (ordnance), presumably from naval maneuvers that frequently occur in the canyon, and scientific equipment such as the lost autonomous ocean glider reported by Trotter et al. (2019).

Dive 327 explored the flat continental shelf from ~670 to 740 m in the northernmost site, imaging ~2700 m of the seafloor. The benthic macro-litter observed consisted of three items (Figs. 2–4, Table 1), the density being 1.11 items km^{-1}. At the juncture of the two main limbs of the canyon, dive 328 surveyed ~2600 m of seabed from the floor up along the steep walls of the canyon at depths between 1790 and 2260 m. The density of litter was the highest recorded in the area at 4.21 items km^{-1}. The 11 items identified were mostly plastics (10), represented by bags, cups, and straps, together with a metal ordnance component. The deepest dive (329) surveyed the canyon floor towards the mouth of the canyon, between ~2550 and 3000 m. This site hosted the largest number of macro-litter items observed in the Perth Canyon (1.40 items km^{-1}), with 6 items representing metal, aluminium, glass, fabric, and military ordnance categories. The presence of macro-litter was consistently lower in the ~2600 m long track of Dive 331, which explored intermediate depths of the west wall of the Perth Canyon's east limb between depths of ~770 and 1130 m, with only one fabric item identified (0.38 items km^{-1}).

With respect to impacts on biota, we did not observe any obvious harm to the local fauna. Many items lie on muddy/silty bottoms, at times even acting as shelter to vagrant megafauna (Fig. 6C). The impact of long lines, however, may be different since DFG can potentially entangle erect sponges and cnidarians; yet no such interaction was observed. The lines were bio-fouled by epizooans (Fig. 8B,C), as was the abandoned fish trap (Fig. 8A).

During the first mission to the Perth Canyon in 2015, an unsuccessful attempt was made to retrieve an autonomous ocean glider from the seafloor, lost by a previous scientific expedition (Fig. 8D). Other attempts of recovering macro-litter at depth were also carried out during the survey of the BCS with partial success (Fig. 8E, F).

4. Discussion

ROV video records provide evidence of benthic macro-litter in the submarine canyon environments located off southwestern Australia. In terms of anthropogenic impacts on the sea bottom, the portions of the canyons explored are remarkably pristine. In fact, quantitative comparative analyses reveal that macro-litter densities are lower than most of the other canyon systems known globally (Fig. 5, Table 2). This is especially the case in the Bremer canyon systems where only 18 items were identified in >16 km of seafloor surveyed. Most of the macro-litter observed in the BCS is hypothesized to be sourced next to its present location. DFG represent the overwhelming majority of identified items (12 out of 18). These were, however, exclusively observed in the shallowest portion of the Hood Canyon (~180–390 m) where the seabed hosts flourishing animal forests dominated by sponges and populated by benthic vagile organisms as well as a diverse fish fauna, some being potential targets of fishing activities. Yet, the pressure on benthic biota is minimal, with no visible damage to the local benthic fauna, which is contrary to that commonly observed in many other submarine canyons. Evidence of impacts from fishing equipment on benthic biota populating submarine canyon systems are, indeed, common in the literature, which document damage to habitats by gear under tension that is entangled around rocky obstacles and sessile species (e.g., Fabri et al., 2014; Galgani et al., 2018; Consoli et al., 2020).

Other macro-litter items were occasionally observed, with plastic being the second most frequent category. For instance, plastic (polymer)

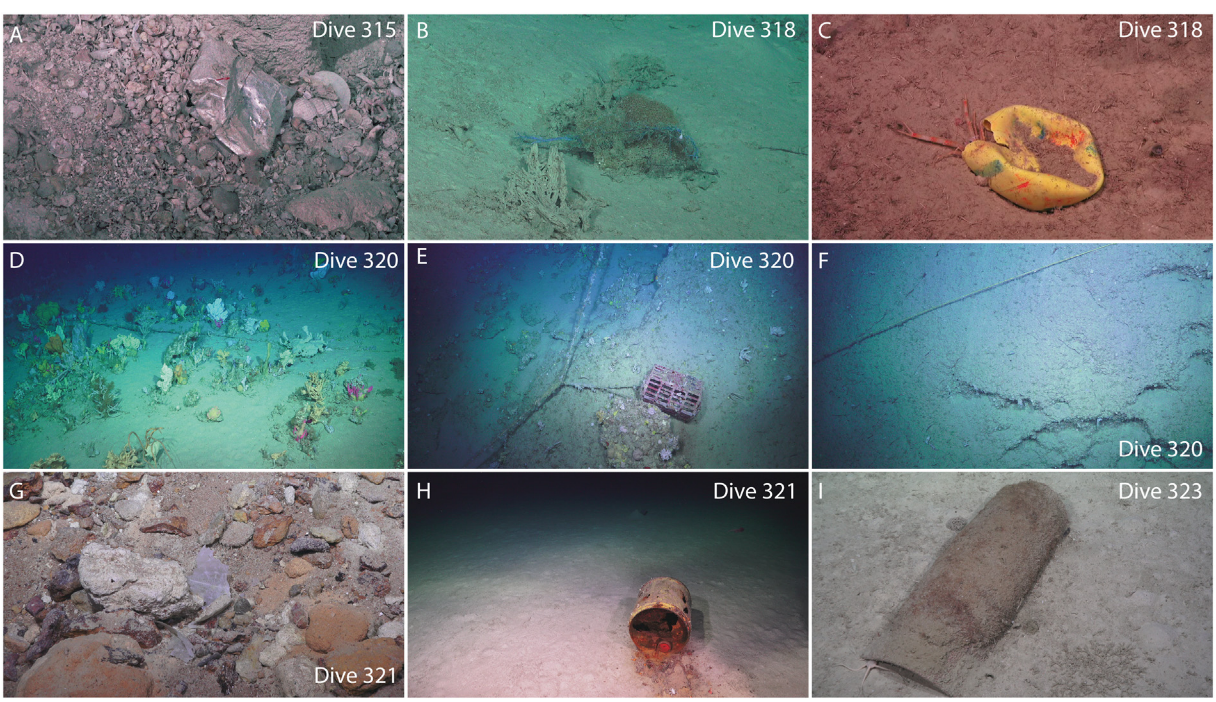

Fig. 6. Examples of benthic macro-litter in the Bremer canyon systems: (A) plastic (or plastic/foil) bag lying on a gravelly bottom at 1531 m, Hood Canyon; (B) nylon net at 459 m, Hood Canyon; (C) plastic ball on soft bottom at ~490 m: it provided shelter to a squat lobster (family Galatheidae), Hood Canyon; (D) longline on bottoms rich in sponges at ~290 m, Hood Canyon; (E) derelict fishing gear entangled on rocky bottom at 267 m, Hood Canyon; (F) longline entangled on the bedrock draped by mud at 357 m, Hood Canyon; (G) unclassified items (likely plastic) associated with rocky blocks and gravel at ~2950 m, Henry Canyon; (H) metal barrel at 2590 m, Henry Canyon; (I) plastic pipe on soft bottom at 1118 m, Hood Canyon.

Fig. 7. Examples of macro-litter items identified in the Perth Canyon. (A-C), from left: metal strip, glass bottle and aluminium can on the continental shelf between 670 and 740 m; (D-I) items identified between 1790 and 2260 m, including plastic bags (D-G), plastic cup (H) and discarded ordnance (I); (L-P) macro-litter on soft bottom imaged in the deepest dive (2550–3000 m): metal container with lid (L); glass bottle (M), fabric glove (N), discarded ordnance (O), mixed class, observed at 2630 m, aluminium can (P); deteriorated fabric at 1082 m (Q).

compounds, such as bags and cups, represented the most abundant macro-litter category in the Perth Canyon, accounting for more than half of the items observed along the 12 km of seafloor explored. Metal, glass, and fabric were also detected, together with mixed materials and aluminium objects to a lesser extent. We hypothesize that benthic macro-litter observed in the Perth Canyon was primarily discarded at sea by ship and boat activity (e.g. commercial, local, and tourism traffic), which is intense in this area given its proximity to a major port (Port Fremantle) and the Western Australian state capital city of Perth (https://www.operations.amsa.gov.au/Spatial/DataServices/MapProduct). In principle, litter floating from the shore and/or wind-blown (Bergmann et al., 2022) could ultimately contribute to deep seabed pollution. Specific hydrographic patterns and increased downslope currents characterize submarine canyons as preferential pathways for the transport of macro-litter to the deep sea (Pham et al., 2014). Recent long-term studies reported a significant increase in the quantities of debris with time (e.g., Mediterranean French canyons, Gerigny et al., 2019), suggesting a relationship with land-based human activities.

We attribute the overall limited impacts on the SW Australian canyon systems explored to be partially related to their important status as commonwealth marine parks, which ensures some restrictions of human activities within these areas. In addition, the lower density of coastal human activities in SW Australia compared to other regions (e.g., the Mediterranean French coast) is consistent with the limited transport of debris towards the deep environment through canyon systems.

It must be acknowledged that the variety of methods used to quantify benthic macro-litter reported in the literature impedes comprehensive comparisons between different areas, which ultimately limits the conclusions that can be drawn from litter found in submarine canyons.

Although most of the studies rely on information from visual surveys, quantities are reported both as counts or weight standardized by area (kg or item km^{-2}) and linear distance (kg or items km^{-1}). If the former provides a more precise estimation of litter density, deriving the exact aerial extension of the portion of seabed imaged during the surveys may be problematic due to the absence of known-distance indicators (e.g., lasers), variations in the orientation of the vehicle, distance from the bottom, and angle of the cameras.

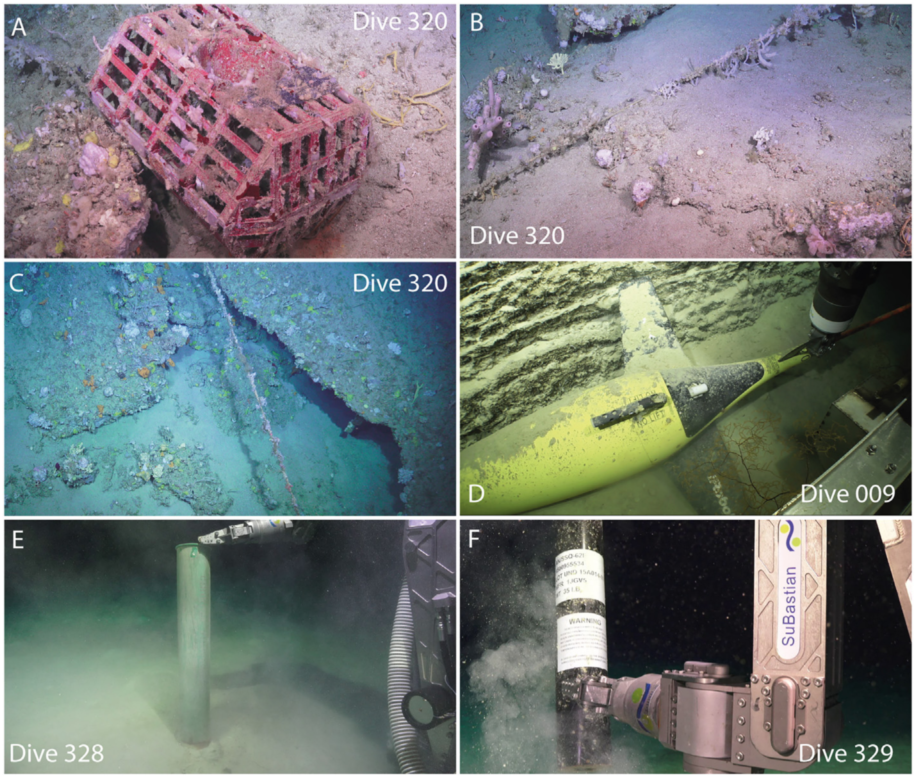

Fig. 8. A-C: Benthic macro-litter biofouling; derelict fishing gear in Dive 320 at 290 m (A), 267 m (B) and 270 m (C) fouled by sponges and bryozoans; (D-F): attempts to remove macro-litter from the seabed; failed attempt of recovering a lost glider during the Perth Canyon 2015 cruise (D) (this site was named after it in McCulloch et al., 2017 and Trotter et al., 2019); recovery of a metallic item in Dive 328 at 2240 m (E), failed, and of a discharged ordnance at 2632 m, successful (F).

Acknowledging recent valuable efforts comparing and evaluating the impact of litter in submarine canyons using literature records (Hernandez et al., 2022), a framework to effectively compare studies and data is still lacking.

Implementing standardized methodologies for the detection, quantification, and characterization of debris in the marine environment is therefore critical to advance our understanding of the presence of benthic macro-litter in submarine canyons and deep-sea environments in general.

5. Conclusions

Albeit limited in spatial coverage and only related to macro-litter (i.e., excluding potential chemical pollution and micro-litter), this study suggests that the current condition of the Bremer canyon systems and Perth Canyon, in terms of visible anthropogenic impacts, is very limited and partly due to their national status as marine parks. This first quantitative analysis, documenting the typology and intensity of human-related impacts, not only reflects their successful stewardship but also represents a baseline for future assessment of the environmental status of benthic communities in these marine parks. Importantly, good management programs must be ongoing and continually re-assessed to ensure their veracity and to at least maintain this low level of impacts, so the future value of these vulnerable ecosystems is guaranteed.

CRediT authorship contribution statement

Marco Taviani: Conceptualization, Investigation, Writing- Original draft preparation; **Federica Foglini**: Investigation, Formal analysis, Data curation, Methodology, Conceptualization, Writing; **Giorgio Castellan**: Methodology, Formal analysis, Visualization, Conceptualization, Writing; **Julie Trotter**: Project administration, Resources, Funding acquisition, Supervision, Investigation, Data curation, Editing; **Paolo Montagna**: Supervision, Investigation, Data curation; **Malcom McCulloch**: Investigation, Data collection. All authors read and approved the submitted manuscript.

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Data availability

Multi beam data are available at MGDS global repository https://www.marine-geo.org/index.php. Squidle annotations are available at https://soi.squidle.org/.

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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References

Akhir, M.F., Pattiaratchi, C., Meuleners, M., 2020. Dynamics and seasonality of the Leeuwin current and the surrounding counter-current system in the region south of Western Australia. J. Mar. Sci. Eng. 8, 552. https://doi.org/10.3390/jmse8080552.

Amaro, T., Huvenne, V.A.I., Allcock, A.L., Aslam, T., Davies, J.S., Danovaro, R., De Stigter, H.C., Duineveld, G.C.A., Gambi, C., Gooday, A.J., Gunton, L.M., Hall, R., Howell, K.L., Ingels, J., Kiriakoulakis, K., Kershaw, C.E., Lavaleye, M.S.S., Robert, K., Stewart, H., Van Rooij, D., White, M., Wilson, A.M., 2016. The Whittard Canyon – a case study of submarine canyon processes. Prog. Oceanogr. 146, 38–57. https://doi.org/10.1016/j.pocean.2016.06.003.

Andrady, A.L., 2011. Microplastics in the marine environment. Mar. Pollut. Bull. 62, 1596–1605. https://doi.org/10.1016/j.marpolbul.2011.05.030.

Angeletti, L., Taviani, M., Canese, S., Foglini, F., Mastrototaro, F., Argnani, A., Trincardi, F., Bakran-Petricioli, T., Ceregato, A., Chimienti, G., 2014. New deep-water cnidarian sites in the southern Adriatic Sea. Mediterr. Mar. Sci. 263–273.

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. https://doi.org/10.1016/j.scitotenv.2021.147745.

Appah, J.K.M., Killeen, O., Lim, A., O'Riordan, R., O'Reilly, L., Wheeler, A.J., 2022. Accumulation of marine litter in cold-water coral habitats: a comparative study of two irish special areas of conservation,NE Atlantic. Mar. Pollut. Bull. 180, 113764. https://doi.org/10.1016/j.marpolbul.2022.113764.

van den Beld, I.M.J., Guillaumont, B., Menot, L., Bayle, C., Arnaud-Haond, S., Bourillet, J.-F., 2017. Marine litter in submarine canyons of the Bay of Biscay. Deep Sea Res. Part II Top. Stud. Oceanogr., Towards Ecosystem Based Management and Monitoring of the Deep Mediterranean, North-East Atlantic and Beyond 145, 142–152. https://doi.org/10.1016/j.dsr2.2016.04.013.

Bergmann, M., Gutow, L., Klages, M. (Eds.), 2015. Marine Anthropogenic Litter. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-16510-3.

Bergmann, M., Wirzberger, V., Krumpen, T., Lorenz, C., Primpke, S., Tekman, M.B., Gerdts, G., 2018. The Arctic Deep Sea - a sink for microplastic? EPIC36th International Marine Debris Conference, San Diego, USA, 2018-03-12-2018-03-16. Presented at the 6th International Marine Debris Conference, San Diego, USA

Bergmann, M., Collard, F., Fabres, J., Gabrielsen, G.W., Provencher, J.F., Rochman, C.M., van Sebille, E., Tekman, M.B., 2022. Plastic pollution in the Arctic | Nature Reviews Earth & Environment. Nat. Rev. Earth Environ. 3 (May 2022), 323.

Botero, C.M., Zielinski, S., Pereira, C.I., León, J.A., Dueñas, L.F., Puentes, V., 2020. The first report of deep-sea litter in the South-Western Caribbean Sea. Mar. Pollut. Bull. 157, 111327. https://doi.org/10.1016/j.marpolbul.2020.111327.

Buhl-Mortensen, L., Buhl-Mortensen, P., 2017. Marine litter in the Nordic Seas: distribution composition and abundance. Mar. Pollut. Bull. 125, 260–270. https://doi.org/10.1016/j.marpolbul.2017.08.048.

Buhl-Mortensen, P., Buhl-Mortensen, L., 2018. Impacts of bottom trawling and litter on the seabed in Norwegian waters. Front. Mar. Sci. 5 (42). https://doi.org/10.3389/fmars.2018.00042.

Butterworth, A., Clegg, I., Bass, C., 2012. Marine debris: a global picture of the impact on animal welfare and of animal-focused solutions. WSPA International, 222 Grays Inn Road, London, WC1X 8HB.

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., Jack, M.E.M., Giorgetti, A., 2021. The quest for seafloor macrolitter: a critical review of background knowledge, current methods and future prospects. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/abc6d4.

Cau, A., Alvito, A., Moccia, D., Canese, S., Pusceddu, A., Rita, C., Angiolillo, M., Follesa, M.C., 2017. Submarine canyons along the upper Sardinian slope (Central Western Mediterranean) as repositories for derelict fishing gears. Mar. Pollut. Bull. 123, 357–364. https://doi.org/10.1016/j.marpolbul.2017.09.010.

Ceccarelli, D.M., 2009. Impacts of Plastic Debris on Australian Marine Wildlife (Report by C&R Consulting for the Department of the Environment, Water, Heritage and the Arts) Australia.

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. https://doi.org/10.1016/j.marpol.2018.03.022.

Chimienti, G., Angeletti, L., Furfaro, G., Canese, S., Taviani, M., 2020. Habitat, morphology and trophism of Tritonia callogorgiae sp. nov., a large nudibranch inhabiting Callogorgia verticillata forests in the Mediterranean Sea. Deep Sea Res. Part Oceanogr. Res. Pap. 165, 103364. https://doi.org/10.1016/j.dsr.2020.103364.

Cleland, J., Kazanidis, G., Roberts, J.M., Ross, S.W., 2021. Distribution of megabenthic communities under contrasting settings in deep-sea cold seeps near northwest Atlantic canyons. Front. Mar. Sci. 8.

Consoli, P., Falautano, M., Sinopoli, M., Perzia, P., Canese, S., Esposito, V., Battaglia, P., Romeo, T., Andaloro, F., Galgani, F., Castriota, L., 2018a. Composition and abundance of benthic marine litter in a coastal area of the central Mediterranean Sea. Mar. Pollut. Bull. 136, 243–247. https://doi.org/10.1016/j.marpolbul.2018.09.033.

Consoli, P., Andaloro, F., Altobelli, C., Battaglia, P., Campagnuolo, S., Canese, S., Castriota, L., Cillari, T., Falautano, M., Pedà, C., Perzia, P., Sinopoli, M., Vivona, P., Scotti, G., Esposito, V., Galgani, F., Romeo, T., 2018b. Marine litter in an EBSA (Ecologically or Biologically Significant Area) of the central Mediterranean Sea: abundance, composition, impact on benthic species and basis for monitoring entanglement. Environ. Pollut. 236, 405–415. https://doi.org/10.1016/j.envpol.2018.01.097.

Consoli, P., Sinopoli, M., Deidun, A., Canese, S., Berti, C., Andaloro, F., Romeo, T., 2020. The impact of marine litter from fish aggregation devices on vulnerable marine benthic habitats of the central Mediterranean Sea. Mar. Pollut. Bull. 152, 110928. https://doi.org/10.1016/j.marpolbul.2020.110928.

Cresswell, G.R., Peterson, J.L., 1993. The Leeuwin Current south of Western Australia. Mar. Freshw. Res. 44, 285–303. https://doi.org/10.1071/mf9930285.

D'Onghia, G., Calculli, C., Capezzuto, F., Carlucci, R., Carluccio, A., Maiorano, P., Pollice, A., Ricci, P., Sion, L., Tursi, A., 2016. New records of cold-water coral sites and fish fauna characterization of a potential network existing in the Mediterranean Sea. Mar. Ecol. 37, 1398–1422.

D'Onghia, G., Calculli, C., Capezzuto, F., Carlucci, R., Carluccio, A., Grehan, A., Indennidate, A., Maiorano, P., Mastrototaro, F., Pollice, A., Russo, T., Savini, A., Sion, L., Tursi, A., 2017. Anthropogenic impact in the Santa Maria di Leuca cold-water coral province (Mediterranean Sea): observations and conservation straits. Deep Sea Res.Part II: Top. Stud. Oceanogr. 145, 87–101.

Danovaro, R., Fanelli, E., Canals, M., Ciuffardi, T., Fabri, M.-C., Taviani, M., Argyrou, M., Azzurro, E., Bianchelli, S., Cantafaro, A., Carugati, L., Corinaldesi, C., de Haan, W.P., Dell'Anno, A., Evans, J., Foglini, F., Galil, B., Gianni, M., Goren, M., Greco, S., Grimalt, J., Güell-Bujons, Q., Jadaud, A., Knittweis, L., Lopez, J.L., Sanchez-Vidal, A., Schembri, P.J., Snelgrove, P., Vaz, S., Angeletti, L., Barsanti, M., Borg, J.A., Bosso, M., Brind'Amour, A., Castellan, G., Conte, F., Delbono, I., Galgani, F., Morgana, G., Prato, S., Schirone, A., Soldevila, E., 2020. Towards a marine strategy for the deep Mediterranean Sea: analysis of current ecological status. Mar. Policy 112, 103781. https://doi.org/10.1016/j.marpol.2019.103781.

De Leo, F.C., Smith, C.R., Rowden, A.A., Bowden, D.A., Clark, M.R., 2010. Submarine canyons: hotspots of benthic biomass and productivity in the deep sea. Proc. R. Soc. B Biol. Sci. 277, 2783–2792. https://doi.org/10.1098/rspb.2010.0462.

Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. Mar. Pollut. Bull. 44, 842–852. https://doi.org/10.1016/S0025-326X(02)00220-5.

Dominguez-Carrió, C., Sanchez-Vidal, A., Estournel, C., Corbera, G., Riera, J.L., Orejas, C., Canals, M., Gili, J.-M., 2020. Seafloor litter sorting in different domains of Cap de Creus continental shelf and submarine canyon (NW Mediterranean Sea). Mar. Pollut. Bull. 161, 111744. https://doi.org/10.1016/j.marpolbul.2020.111744.

Duran, E.R., Phillips, H.E., Furue, R., Spence, P., Bindoff, N.L., 2020. Southern Australia Current System based on a gridded hydrography and a high-resolution model. Progr. Oceanogr. 181, 102254. https://doi.org/10.1016/j.pocean.2019.102254.

Enrichetti, F., Dominguez-Carrió, C., Toma, M., Bavestrello, G., Canese, S., Bo, M., 2020. Assessment and distribution of seafloor litter on the deep Ligurian continental shelf and shelf break (NW Mediterranean Sea). Mar. Pollut. Bull. 151, 110872. https://doi.org/10.1016/j.marpolbul.2019.110872.

Fabri, M.-C., Pedel, L., Beuck, L., Galgani, F., Hebbeln, D., Freiwald, A., 2014. Megafauna of vulnerable marine ecosystems in French mediterranean submarine canyons: spatial distribution and anthropogenic impacts. Deep Sea ResPart II Top. Stud. Oceanogr. 104, 184–207.

Fabri, M.-C., Vinha, B., Allais, A.-G., Bouhier, M.-E., Dugornay, O., Gaillot, A., Arnaubec, A., 2019. Evaluating the ecological status of cold-water coral habitats using non-invasive methods: an example from Cassidaigne canyon, northwestern Mediterranean Sea. Prog. Oceanogr. 178, 102172. https://doi.org/10.1016/j.pocean.2019.102172.

Fernandez-Arcaya, U., Ramirez-Llodra, E., Aguzzi, J., Allcock, A.L., Davies, J.S., Dissanayake, A., Harris, P., Howell, K., Huvenne, V.A.I., Macmillan-Lawler, M., Martín, J., Menot, L., Nizinski, M., Puig, P., Rowden, A.A., Sanchez, F., Van den Beld, I.M.J., 2017. Ecological role of submarine canyons and need for canyon conservation: a review. Front. Mar. Sci. 4.

Fine, R.A., 1993. Circulation of Antarctic intermediate water in the South Indian Ocean. Deep Sea ResPart Oceanogr. Res. Pap. 40, 2021–2042. https://doi.org/10.1016/0967-0637(93)90043-3.

Fleet, D., Vlachogianni, T., Hank, G., 2021. A Joint List of Litter Categories for Marine Macrolitter Monitoring. EUR 30348 EN. 2021. Publications Office of the European Union, Luxembourg 978-92-76-21445-8. https://doi.org/10.2760/127473 JRC121708.

Galgani, F., 2015. Marine litter, future prospects for research. Front. Mar. Sci. 2, 87. https://doi.org/10.3389/fmars.2015.00087.

Galgani, F., Lecomu, F., 2004. Debris on the seafloor at "Hausgarten". In: Klages, Michael, Thiede, Jörn, Foucher, Jean-Paul (Eds.), The Expedition ARKTIS XIX/3 of the Research Vessel POLARSTERN in 2003 - Reports of Legs 3a, 3b and 3c. Berichte zur Polar- und Meeresforschung. 488. AWI, Alfred-Wegener-Institut für Polar- und Meeresforschung, Bremerhaven.

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.

Galgani, F., Leaute, J.P., Moguedet, P., Souplet, A., Verin, Y., Carpentier, A., Goraguer, H., Latrouite, D., Andral, B., Cadiou, Y., Mahe, J.C., Poulard, J.C., Nerisson, P., 2000. Litter on the sea floor along European coasts. Mar. Pollut. Bull. 40, 516–527. 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 https://doi.org/10.1007/978-3-319-16510-3_2.

Galgani, F., Pham, C.K., Claro, F., Consoli, P., 2018. Marine animal forests as useful indicators of entanglement by marine litter. Mar. Pollut. Bull. 135, 735–738. https://doi.org/10.1016/j.marpolbul.2018.08.004.

Galgani, F., Michela, A., Gérigny, O., Maes, T., Tambutté, E., Harris, P.T., 2022. Marine litter, plastic, and microplastics on the seafloor. Plastics and the Ocean. John Wiley & Sons, Ltd, pp. 151–197. https://doi.org/10.1002/9781119768432.ch6.

Gerigny, O., Brun, M., Fabri, M.C., Tomasino, C., Le Moigne, M., Jadaud, A., Galgani, F., 2019. Seafloor litter from the continental shelf and canyons in French Mediterranean water: distribution, typologies and trends. Mar. Pollut. Bull. 146, 653–666. https://doi.org/10.1016/j.marpolbul.2019.07.030.

Giusti, M., Canese, S., Fourt, M., Bo, M., Innocenti, C., Goujard, A., Daniel, B., Angeletti, L., Taviani, M., Aquilina, L., Tunesi, L., 2019. Coral forests and Derelict Fishing Gears in submarine canyon systems of the Ligurian Sea. Prog. Oceanogr. 178, 102186. https://doi.org/10.1016/j.pocean.2019.102186.

Harris, P.T., Whiteway, T., 2011. Global distribution of large submarine canyons: geomorphic differences between active and passive continental margins. Mar. Geol. 285, 69–86.

Grinyó, J., Chevaldonné, P., Schohn, T., Le Brisa, N., 2021. Megabenthic assemblages on bathyal escarpments off the west Corsican margin (Western Mediterranean). Deep-Sea Res. I: Oceanogr. Res. Pap. 171, 103475. https://doi.org/10.1016/j.dsr.2021.103475.

Harris, P.T., Tamelander, J., Lyons, Y., Neo, M.L., Maes, T., 2021. Taking a mass-balance approach to assess marine plastics in the South China Sea. Mar. Pollut. Bull. 171, 112708. https://doi.org/10.1016/j.marpolbul.2021.112708.

Heap, A.D., Harris, P.T., 2008. Geomorphology of the Australian margin and adjacent seafloor. Aust. J. Earth Sci. 55, 555–585. https://doi.org/.1080/08120090801888669.

Hernandez, I., Davies, J.S., Huvenne, V.A.I., Dissanayake, A., 2022. Marine litter in submarine canyons: a systematic review and critical synthesis. Front. Mar. Sci. 9, 965612. https://doi.org/10.3389/fmars.2022.965612.

Ioakeimidis, C., Papatheodorou, G., Fermeli, G., Streftaris, N., Papathanassiou, E., 2015. Use of ROV for assessing marine litter on the seafloor of Saronikos Gulf (Greece): a way to fill data gaps and deliver environmental education. Springerplus 4, 463. https://doi.org/10.1186/s40064-015-1248-4.

Jeftic, L., Sheavly, S.B., Adler, E., Meith, N., 2009. Marine Litter: A Global Challenge. Regional Seas. United Nations Environment Programme, Nairobi, Kenya.

Kazanidis, G., Orejas, C., Borja, A., Kenchington, E., Henry, L.-A., Callery, O., Carreiro-Silva, M., Egilsdottir, H., Giacomello, E., Grehan, A., Menot, L., Morato, T., Rueda, J.L., Stirling, D., Stratmann, T., Van Oevelen, D., Palialexis, A., Johnson, D., Roberts, J.M., Ragnarsson, S.A., 2020. Assessing the environmental status of selected North Atlantic deep-sea ecosystems. Ecol. Indic. 119 (December 2020), 106624. https://doi.org/10.1016/j.ecolind.2020.106624.

Lastras, G., Canals, M., Ballesteros, E., Gili, J.-M., Sanchez-Vidal, A., 2016. Cold-water corals and anthropogenic impacts in La Fonera submarine canyon head, Northwestern Mediterranean Sea. PLOS ONE 11, e0155729. https://doi.org/10.1371/journal.pone.0155729.

McCartney, M.S., 1977. A Voyage of Discovery: George Deacon 70th Anniversary Volume, chap. Subantarctic Mode Water, Supplement to Deep-Sea Research. Pergamon Press, Oxford, pp. 103–119.

McCulloch, M., Trotter, J., Falter, J., Pattiaratchi, C., Montagna, P., Taviani, M., Thresher, R., Hosie, A., Garcia-Corral, L., Haig, D., Foglini, F., Agusti, S., Durate, C., 2017. ROV Exploration of the Perth Canyon and Assessing the Vulnerability of Deep-Sea Corals to Climate Change and Ocean Acidification. Schmidt Ocean Institute Cruise FK150301 Final Report. Available at:. https://schmidtocean.org/cruise/perth-canyon-first-deep-exploration/.

Mecho, A., Aguzzi, J., Mol, B.D., Lastras, G., Ramirez-Llodra, E., Bahamon, N., Company, J.B., Canals, M., 2018. Visual faunistic exploration of geomorphological human-impacted deep-sea areas of the north-western Mediterranean Sea. J. Mar. Biol. Assoc. U. K. 98, 1241–1252. https://doi.org/10.1017/S0025315417000431.

Mecho, A., Francescangeli, M., Ercilla, G., Fanelli, E., Estrada, F., Valencia, J., Sobrino, I., Danovaro, R., Company, J.B., Aguzzi, J., 2020. Deep-sea litter in the Gulf of Cadiz (Northeastern Atlantic, Spain). Mar. Pollut. Bull. 153, 110969. https://doi.org/10.1016/j.marpolbul.2020.110969.

Middleton, J.F., Bye, J.A.T., 2007. A review of the shelf-slope circulation along Australia's southern shelves: Cape Leeuwin to Portland. Progr. Oceanogr. 75, 1–41. https://doi.org/10.1016/j.pocean.2007.07.001.

Moccia, D., Cau, A., Alvito, A., Canese, S., Cannas, R., Bo, M., Angiolillo, M., Follesa, M.C., 2019. New sites expanding the "Sardinian cold-water coral province" extension: a new potential cold-water coral network? Aquat. Conserv. Mar. Freshw. Ecosyst. 29, 153–160. https://doi.org/10.1002/aqc.2975.

Molinelli, E.J., 1981. The Antarctic influence on Antarctic intermediate water. J. Mar. Res. 39, 267–293.

Mordecai, G., Tyler, P.A., Masson, D.G., Huvenne, V.A.I., 2011. Litter in submarine canyons off the west coast of Portugal. Deep Sea Res. Part II Top. Stud. Oceanogr., The Geology, Geochemistry, and Biology of Submarine Canyons West of Portugal 58, 2489–2496. https://doi.org/10.1016/j.dsr2.2011.08.009.

Oliveira, F., Monteiro, P., Bentes, L., Henriques, N.S., Aguilar, R., Gonçalves, J.M.S., 2015. Marine litter in the upper São Vicente submarine canyon (SW Portugal): abundance, distribution, composition and fauna interactions. Mar. Pollut. Bull. 97, 401–407. https://doi.org/10.1016/j.marpolbul.2015.05.060.

Orejas, C., Gori, A., Iacono, C.L., Puig, P., Gili, J.-M., Dale, M.R., 2009. Cold-water corals in the Cap de Creus canyon, northwestern Mediterranean: spatial distribution, density and anthropogenic impact. Mar. Ecol. Prog. Ser. 397, 37–51.

Peng, L., Fu, D., Qi, H., Lan, C.Q., Yu, H., Ge, C., 2020. Micro- and nano-plastics in marine environment: source, distribution and threats — a review. Sci. Total Environ. 698, 134254. https://doi.org/10.1016/j.scitotenv.2019.134254.

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., Rooij, D.V., Tyler, P.A., 2014. Marine litter distribution and density in European seas, from the shelves to deep basins. PLOS ONE 9, e95839. 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. https://doi.org/10.1038/s41598-019-41816-8.

Pierdomenico, M., Casalbore, D., Chiocci, F.L., 2020. The key role of canyons in funnelling litter to the deep sea: a study of the Gioia Canyon (Southern Tyrrhenian Sea). Anthropocene 30, 100237. https://doi.org/10.1016/j.ancene.2020.100237.

Pohl, F., Eggenhuisen, J.T., Kane, I.A., Clare, M.A., 2020. Transport and burial of microplastics in deep-marine sediments by turbidity currents. Environ. Sci. Technol. 54, 4180–4189. https://doi.org/10.1021/acs.est.9b07527.

Prampolini, M., Angeletti, L., Grande, V., Taviani, M., Foglini, F., 2020. Chapter 48 - Tricase Submarine Canyon: cold-water coral habitats in the southwesternmost Adriatic Sea (Mediterranean Sea). In: Harris, P.T., Baker, E. (Eds.), Seafloor Geomorphology as Benthic Habitat, Second edition Elsevier, pp. 793–810.

Quattrini, A.M., Nizinski, M.S., Chaytor, J.D., Demopoulos, A.W.J., Roark, E.B., France, S.C., Moore, J.A., Heyl, T., Auster, P.J., Kinlan, B., Ruppel, C., Elliott, K.P., Kennedy, B.R.C., Lobecker, E., Skarke, A., Shank, T.M., 2015. Exploration of the canyon-incised continental margin of the Northeastern United States reveals dynamic habitats and diverse communities. PLOS ONE 10, e0139904. https://doi.org/10.1371/journal.pone.0139904.

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. 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., Integrated Study of a Deep Submarine Canyon and Adjacent Open Slopes in the Western Mediterranean Sea: An Essential Habitat 118, 273–287. https://doi.org/10.1016/j.pocean.2013.07.027.

Reisser, J., Shaw, J., Wilcox, C., Hardesty, B.D., Proietti, M., Thums, M., Pattiaratchi, C., 2013. Marine plastic pollution in waters around Australia: characteristics, concentrations, and pathways. PLOS ONE 8, e80466. https://doi.org/10.1371/journal.pone.0080466.

Robertson, C.M., Demopoulos, A.W.J., Bourque, J.R., Mienis, F., Duineveld, G.C.A., Lavaleye, M.S.S., Koivisto, R.K.K., Brooke, S.D., Ross, S.W., Rhode, M., Davies, A.J., 2020. Submarine canyons influence macrofaunal diversity and density patterns in the deep-sea benthos. Deep Sea Res. Part Oceanogr. Res. Pap. 159, 103249. https://doi.org/10.1016/j.dsr.2020.103249.

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 ResPart Oceanogr. Res. Pap. 79, 96–105. https://doi.org/10.1016/j.dsr.2013.05.006.

Silva, M.V.B., Araújo, T.C.M., 2021. The South American advances in submarine canyons studies and their link to the ocean decade. Front. Mar. Sci. 8.

Sloyan, B.M., Rintoul, S.R., 2001. The southern ocean limb of the global deep overturning circulation. J. Phys. Oceanogr. 31, 143–173. https://doi.org/10.1175/1520-0485(2001)031<0143:TSOLOT>2.0.CO;2.

Spedicato, M.T., Zupa, W., Carbonara, P., Fiorentino, F., Follesa, M.C., Galgani, F., et al., 2019. Spatial distribution of marine macro-litter on the seafloor in the northern Mediterranean Sea: the MEDITS initiative. Sci. Mar. 83, 257–270. https://doi.org/10.3989/scimar.04987.14a.

Taviani, M., Angeletti, L., Canese, S., Cannas, R., Cardone, F., Cau, A., Cau, A.B., Follesa, M.C., Marchese, F., Montagna, P., 2017. The "Sardinian cold-water coral province" in the context of the Mediterranean coral ecosystems. Deep Sea Res. Part II Top. Stud. Oceanogr. 145, 61–78.

Taviani, M., Angeletti, L., Cardone, F., Montagna, P., Danovaro, R., 2019. A unique and threatened deep water coral-bivalve biotope new to the Mediterranean Sea offshore the Naples megalopolis. Sci. Rep. 9, 3411. https://doi.org/10.1038/s41598-019-39655-8.

Tekman, M.B., Walther, Bruno A., Peter, Corina, Gutow, Lars, Bergmann, Melanie, 2022. Impacts of Plastic Pollution in the Oceans on Marine Species, Biodiversity and Ecosystems. Zenodo. https://doi.org/10.5281/ZENODO.5898683.

Trotter, J.A., Pattiaratchi, C., Montagna, P., Taviani, M., Falter, J., Thresher, R., Hosie, A., Haig, D., Foglini, F., Hua, Q., McCulloch, M.T., 2019. First ROV exploration of the Perth Canyon: canyon setting, faunal observations, and anthropogenic impacts. Front. Mar. Sci. 6.

Trotter, J., Montagna, P., Taviani, M., Sadekov, A., Skrzypek, G., Foglini, F., Mazzoli, C., Remia, A., Hosie, A., Hara, A., Pattiaratchi, C., McCulloch, M., 2021. ROV Exploration of deep-water coral habitats of Southwest Australian submarine canyons - Schmidt Ocean Institute Cruise FK200126. Final Report. Available at:. https://schmidtocean.org/wp-content/uploads/FK200126_SW-Canyons-Final-Report_02072021.pdf.

Trotter, J.A., Taviani, M., Foglini, F., Sadekov, A., Skrzypek, G., Mazzoli, C., Remia, A., Santodomingo, N., Castellan, G., McCulloch, M., Pattiaratchi, C., Montagna, P., 2022. Unveiling deep-sea habitats of the Southern Ocean-facing submarine canyons of southwestern Australia. Progr. Oceanogr. (In press).

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. https://doi.org/10.1016/j.pocean.2015.03.013.

UNESCO, 2021. United Nations Decade of Ocean Science for Sustainable Development (2021-2030). https://en.unesco.org/ocean-decade (last accessed 18 May 2022).

Watters, D.L., Yoklavich, M.M., Love, M.S., Schroeder, D.M., 2010. Assessing marine debris in deep seafloor habitats off California. Mar. Pollut. Bull. 60, 131–138. https://doi.org/10.1016/j.marpolbul.2009.08.019.

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. https://doi.org/10.1016/j.marpolbul.2012.02.015.

Wijeratne, S., Pattiaratchi, C., Proctor, R., 2018. Estimates of surface and subsurface boundary current transport around Australia. J. Geophys. Res. Oceans 123, 3444–3466. https://doi.org/10.1029/2017JC013221.

Wong, A.P.S., 2005. Subantarctic mode water and antarctic intermediate water in the South Indian Ocean based on profiling float data 2000–2004. J. Mar. Res. 63, 789–812. https://doi.org/10.1357/0022240054663196.

Woo, L.M., Pattiaratchi, C., 2008. Hydrography and water masses off the western Australian coast. Deep Sea Res. - OceanogrRes. Pap. 55, 1090–1104. https://doi.org/10.1016/j.dsr.2008.05.005.

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. Front. Mar. Sci. 2 (last accessed 18 May 2022).

Zhong, G., Peng, X., 2021. Transport and accumulation of plastic litter in submarine canyons -the role of gravity flows. Geology 49, 581–586. https://doi.org/10.1130/G48536.1.