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The combined role of near-bed currents and sub-seafloor processes in the transport and pervasive burial of microplastics in submarine canyons

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ABSTRACT

Submarine canyons are important conduits for microplastic transport to the deep sea, but the processes involved in that transport and how faithfully seafloor deposits record trends in pollution remain unclear. We use sediment push-cores for microplastic and sediment grain-size analysis from two transects across the Whittard Canyon, UK, to investigate the roles of near-bed flows and sub-seafloor processes in the transport and burial of microplastics and semi-synthetic microfibrils. Microplastic and microfibre pollution is pervasive across the canyon at both transects, from the thalweg and from 500 m higher on the flanks, despite turbidity currents

being confined to the canyon thalweg. We calculate sediment accumulation rates from ^{210}Pb dating and show that microplastic concentrations remain similar at sediment depths down to 10 cm. Throughout the Whittard Canyon there is an observed uniformity in the gradual decline in microfibre concentration with sediment depth, despite the variable sample locations and marked variations in sediment accumulation rates. Furthermore, the huge global increase in plastic production rates over time is not recorded, and microplastics are present in sediments that pre-date the mass-production of plastic. The interaction of turbidity currents, deep tidally-driven currents, and sub-seafloor processes affects microfibre burial processes in the deep sea and shreds any potential signal that microplastics may provide as indicators of historical plastic production rates; complicating the use of microplastics as fully-reliable markers of Anthropocene onset.

Introduction

Plastic production increased 700%, from 50 million tonnes (Mt) in the 1970's to >400 Mt in 2022 (PlasticsEurope, 2023). More than 10 Mt of plastic enters the World's ocean annually (Lebreton *et al.*, 2017). Microplastics (<1 mm diameter particles) represent ~13.5% of the marine plastic budget (Koelmans *et al.*, 2017), including primary (manufactured particles; Zitko and Hanlon, 1991) and secondary (derived from the breakdown of macroplastics; Andrady, 2011) microplastics. Semi-synthetic microfibres (*e.g.*, composed of rayon and chlorinated rubber) are also persistent in the natural environment (Athey and Erdle, 2022; Finnegan *et al.*, 2022), are observed in deep-sea sediments (Woodall *et al.*, 2014), and have similar detrimental effects on biota (Jiang *et al.*, 2024) as plastic microfibres. Semi-synthetic microfibres are commonly used in clothes manufacturing (*e.g.*, Napper and Thompson, 2016) and cigarette filters (*e.g.*, Belzagui *et al.*, 2021). Therefore, we use 'microfibre' to encompass

synthetic and semi-synthetic microfibrils, and ‘anthropogenic microparticles’ to encompass both microplastic particles and microfibrils.

Lacustrine and shallow-marine settings act as archives to calculate the rate and quantity of pollutant delivery (such as anthropogenic microparticles) and allow monitoring of how stresses on ecosystems change over time (Brandon *et al.*, 2019; Uddin *et al.*, 2021 and references therein). Few studies have acquired sedimentary time-series records of anthropogenic microparticles in the deep sea (*e.g.*, Chen *et al.*, 2020), despite it being the ultimate sink for plastics (Thompson *et al.*, 2004; Woodall *et al.*, 2014; Koelmans *et al.*, 2017; Choy *et al.*, 2019). Furthermore, none exist in submarine canyons, the main conduits for delivering particulate matter (Normark, 1970; Talling *et al.*, 2023), including pollutants (Paull *et al.*, 2002; Zhong and Peng, 2021; Pierdomenico *et al.*, 2023) from terrestrial and coastal settings to the deep sea, and hosts to important seafloor ecosystems (Treigner *et al.*, 2006; Fernandez-Arcaya *et al.*, 2017). Avalanches of sediment, known as turbidity currents, flow through submarine canyons and are responsible for generating Earth’s largest sediment accumulations (Curry and Moore, 1971). These flows are thought to be the main agent for anthropogenic microparticle transfer to, and sequestration on, the deep seafloor (Kane and Clare, 2019; Pohl *et al.*, 2020; Rohais *et al.*, 2024; Zhang *et al.*, 2024; Chen *et al.*, 2025). However, it is increasingly recognised that other hydrodynamic processes can also affect anthropogenic microparticle concentrations in the deep sea (*e.g.* Kane *et al.*, 2020), as well as the transport and burial of particulate matter in submarine canyons (*e.g.*, Maier *et al.*, 2019; Bailey *et al.*, 2024; Hage *et al.*, 2024; Palanques *et al.*, 2024). It is possible that the importance of these processes has been underestimated, and therefore, that the role of hydrodynamic and sub-seafloor processes, and human activities on anthropogenic microparticle dispersal and burial in submarine canyons remains unconstrained. Here, we consider the sub-seafloor as the tens of centimetres below the seafloor sediments. This uncertainty results from a lack of

targeted seafloor sampling and sedimentological context, therefore limiting our understanding of anthropogenic microparticle fluxes to the deep sea, threats to deep-seafloor ecosystems, and deep-sea anthropogenic sedimentary archives.

In addition to anthropogenic microparticle transport via turbidity currents, we hypothesise that other hydrodynamic (*e.g.*, internal tides), anthropogenic (*e.g.*, seabed trawling), and biological (*e.g.*, bioturbation) processes work to (re-)distribute and bury pollutants across wide areas in submarine canyon systems. We aim to tie anthropogenic microparticle distribution with concepts of deep-water process sedimentology to determine the interplay of anthropogenic microparticle transport and burial processes in the deep sea. using a targeted seafloor sampling dataset from two transects across Whittard Canyon. We assess these process interactions by integrating detailed seafloor observations from multibeam bathymetric mapping and video footage acquired from a Remotely Operated Vehicle (ROV), with analysis of near-seafloor sediments sampled at 4 box-core locations to quantify sediment accumulation rates, and at 9 precisely-located ROV push-core locations to quantify the sediment grain-size and anthropogenic microparticle concentration in seafloor sediments. To test the hypothesis, and meet this aim, the following objectives are addressed: i) to map the distribution and concentration of anthropogenic microparticles throughout a branch of the Whittard Canyon, ii) to document changes in anthropogenic microparticle concentration with burial depth, iii) to assess sediment grain-size trends associated with the anthropogenic microparticle distribution and concentration, and integrate the findings with sediment accumulation rates, and iv) to discuss how anthropogenic microparticle transport and burial processes controls their transfer in submarine canyons.

Setting and methods

Whittard Canyon

The head of Whittard Canyon lies at ~200 m water depth in the Celtic Sea, NE Atlantic, ~300 km from the nearest coast (Fig. 1A). Four main tributary branches incise steeply into the shelf break. The canyon extends oceanward for ~150 km, to ~3800 m water depth (Amaro *et al.*, 2016). The upper-canyon reach of the Eastern Branch extends ~55 km, from the head to ~2960 m water depth, with steep canyon flanks and a $>2^\circ$ thalweg slope, with a vertical relief from flank to thalweg of ~1000 m (Fig. 1B, C and E). The lower-canyon reach extends to ~3800 m water depth, with lower gradient canyon flanks and a $<2^\circ$ thalweg slope, with a vertical relief from flank to thalweg of ~1250 m (Fig. 1B, C and E). Further details of the canyon's geomorphology and bathymetry are included in the Supplemental Material.

Fishing activity on the Celtic Margin

Fishing activities that disturb the seafloor (*i.e.*, benthic trawling) are common around the head of Whittard Canyon, and on many of its interfluvies (Fig. 2). Bottom trawling activity can be a source of marine pollutants (Xue *et al.*, 2020) and causes sediment resuspension (Daly *et al.*, 2018). The cumulative annual benthic trawling effort for 2013-2014 and 2023-2024 was exported from GlobalFishingWatch (2024) for an area of 16,650 km² (48° - 49° N to 9° - 11° W) around the continental shelf, and Whittard Canyon (Fig. 2A and B). The trawling effort for the same period for the 661 km² (48° 10' 2.56" - 48° 29' 59.74" N to 9° 33' 34.59" - 9° 47' 52.25" W) area covered by The Canyons Marine Conservation Zone was also exported (Fig. 2C and D). The Marine Conservation Zone was designated in November 2013 for the features

‘Cold-water coral reef’ and ‘Deep seabed’, following identification of vulnerable ecosystems in the area (Davies *et al.*, 2014). Later on, two further features were added to the site designation: ‘Coral gardens’ and ‘Sea-pen and burrowing megafauna communities’. The intensity of benthic trawling on the Celtic Margin increased fivefold in the ten-year period from 2013-2014 to 2023-2024 (GlobalFishingWatch, 2024; Fig. 2), but was banned in the majority of The Canyons MCZ in June 2022 as new fisheries management measures were implemented. In March 2023, the Irish sector of the Whittard Canyon was declared a candidate Special Area of Conservation, particularly for the protection of the Annex I habitat type ‘reefs’ (NPWS, 2023). However, fishing with bottom-contact gear has been banned in EU waters below 800 m water depth since 2017, with a further ban between 400 and 800 m in selected areas brought in in 2022 to protect vulnerable marine ecosystems (EU, 2022).

Hydrodynamic mooring

A moored, downward-looking, 600 kHz Acoustic Doppler Current Profiler (M1 mooring – Fig. 1B: 30 m above seafloor; 1500 m water depth) was deployed in the Eastern Branch and recorded near-bed hydrodynamic conditions from June 2019 – June 2020, including vigorous (up to 1 ms^{-1}) internal tides and 6 turbidity currents. These turbidity currents had maximum down-canyon velocities of $1.5\text{--}5.0 \text{ ms}^{-1}$, flow thicknesses $>30 \text{ m}$, and accumulated quartz-rich, fine sand in a sediment trap 10 m above seafloor (Heijnen *et al.*, 2022; Chen *et al.*, 2025; Fig. 3B). The frequency and velocity of the turbidity currents recorded by the ADCP during the sampling period document how the Whittard Canyon experiences turbidity current activity analogous in frequency and velocity to many land-attached canyons, despite being land-detached (Heijnen *et al.*, 2022; Talling *et al.*, 2023).

Sediment push-core recovery

Five precisely located push-cores were collected using the ROV 'ISIS' during expedition JC237 on board the RRS *James Cook* (Huvenne, 2024), along an across-canyon transect in the upper-canyon reach (24.9 km from the head, 1062-1546 m water depth) from 34 metres above thalweg (m.a.t.) to 521 m.a.t. on the canyon flank. Four precisely located push-cores were also collected from an across-canyon transect in the lower-canyon reach (62.3 km from the head, 2773-3204 m water depth) (Fig. 1B, D and E) from 0 m.a.t. to 431 m.a.t. on the canyon flank. In doing so, the two distinct physiographic domains, with respect to the amount of canyon confinement provided by the gradient of the canyon flanks and canyon thalweg of Whittard Canyon, are extensively sampled. Expanding on the study by Chen *et al.* (2025) where push-cores were collected along a down-thalweg transect, the current study uses two across-canyon transects. These across-canyon transects were positioned to constrain anthropogenic microparticle distribution and concentration with increasing height and distance from the thalweg, where hydrodynamic processes other than turbidity currents are active. The push-cores were recovered from the upper canyon-transect on the 21st August 2022, and from the lower canyontransect on the 2nd September 2022. All 9 push-cores were subsampled at 1 cm depth-intervals, down to 10 cm, depending on core recovery (subsample n=83), for anthropogenic microparticle extraction, and sediment grain-size analysis (Table S1). High-resolution bathymetric data enable investigation of the effects of submarine canyon geomorphology on anthropogenic microparticle distribution.

Laboratory procedures

Anthropogenic microparticle extraction, identification, and quantification

The 1 cm sediment core horizons had variable weights and water content, so samples were dried overnight in a drying oven set to 50°C. The dried samples were weighed, and for comparative purposes the weight and anthropogenic microparticle content were normalised to 50 g dry sediment weight. Sediment samples were then stored in glass beakers covered with aluminium foil. Samples were added to a 1 L glass beaker with ~700 mL of a dense ZnCl₂ solution (1.6 g cm⁻³), disaggregated using a magnetic stirrer, and mixed until homogenized. The microplastics were extracted from the sediment using a polyvinyl chloride Sediment Microplastic Isolation (SMI) unit following a protocol developed for microplastic extraction in a cost-effective, reproducible, and easily portable manner (Coppock *et al.*, 2017). The solution was added to the SMI unit, and the beaker was rinsed with ZnCl₂ solution to flush any remaining sediment/anthropogenic microparticles. Prior to each use, the SMI unit was disassembled and thoroughly rinsed with Class 1 Milli-Q de-ionized water. Following settling overnight, the headspace supernatant was isolated by closing the ball valve of the SMI unit and rinsing with extra ZnCl₂ solution to flush any remaining anthropogenic microparticles before vacuum filtering over a Whatman 541, 22 µm filter paper. The prepared filter paper was then placed in a labelled petri dish and covered. Throughout the extraction procedure, all individuals wore white cotton laboratory coats and latex gloves. All the extraction stages were performed in a clean laboratory in a fume cupboard. When the sediment samples were mixing in the 1 L beaker, and settling in the SMI units, they were covered with aluminum foil to limit airborne contamination. When it was not possible during the sample preparation to cover the sediment sample with aluminium foil, an opened petri dish with a blank, Whatman 541, 22 µm filter paper was placed in the fume cupboard and used as a contamination control procedural blank. When the prepared filter paper was exposed during the identification stage, a second

contamination control procedural blank was also collected, again using an opened petri dish with a blank, Whatman 541, 22 μ m filter paper, placed in the microscopy laboratory (Table S2).

The prepared filter papers, both from the extraction process and the control blanks were analysed in a clean microscopy laboratory using a Zeiss Axio Zoom, V16 stereomicroscope at 20-50X magnification. Here, we define anthropogenic microparticles as between 1 μ m and 1 mm in size; the same size range used by prominent microplastic studies (*e.g.*, Browne *et al.*, 2011; Claessens *et al.*, 2011; Van Cauwenberghe *et al.*, 2013, 2015; Vianello *et al.*, 2013; Dekiff *et al.*, 2014; Kane and Clare, 2019; Kane *et al.*, 2020). Filter papers were traversed systematically to identify anthropogenic microparticles based on the following criteria: (i) no visible cellular or organic structures; (ii) a positive reaction to the hot needle test (de Witte *et al.*, 2014); and (iii) maintenance of structural integrity when touched or moved. Anthropogenic microparticles were categorised based on their colour and type, including, whether they were microfibrils, microplastic fragments (including films), or microbeads (Table S1).

Micro-Fourier Transform Infrared Spectroscopy

Anthropogenic microparticles were visually identified using optical microscopy and a subset of particles were analysed using micro-Fourier transform infrared (μ -FTIR) spectroscopy for polymer confirmation. Identification of polymer composition was conducted on a subsample (n=13) of the extracted microplastics using a PerkinElmer Spotlight 400 FTIR spectrometer using transmittance mode (Fig. 4; Table S3). Further details are included in the Supplemental Material.

Grain-size analysis

The grain-size of 79 of the 83 push-core samples was analysed using a Microtrac FLOWSYNC particle sizer (Microtrac MRB). The grain-size of the four remaining samples (PC060B-E) was analysed using the dry sieving method due to the FLOWSYNC particle sizer having an upper particle limit of 2000 μm , and the fragmented shell material in the samples exceeded this upper limit. The FLOWSYNC particle sizer uses tri-laser diffraction to measure particle size distribution with a lower particle limit size of 0.01 μm . The samples were subjected to a small amount of ultrasonic dispersion. Three aliquots were analysed to ensure that each sample was completely dispersed. The grain-size distribution, indicating the volume percentage of grains in a certain size interval, was constructed (Fig. 3C-K). The grain-size percentiles were exported from the FLOWSYNC software and are documented in Table S1.

²¹⁰Pb sediment accumulation rates

Sediment accumulation rates derived from ²¹⁰Pb dating of box-cores were determined at 4 positions within the upper-canyon reach; 2 in the thalweg and 2 on the canyon flanks (Figs 1 and 5; Table S4). Sediment accumulation rates are calculated from the four box-cores (BC64, BC65, BC72, and BC73) (Fig. 5B-I; Table S4), using ²¹⁰Pb dating. The box-cores were collected during the research cruise 64PE421 conducted by NIOZ (the Royal Netherlands Institute for Sea Research) from the 14th May 2017 – 25th May 2017. The recovery rate of the box-cores varied by location. Further details are included in the Supplemental Material.

Results

Anthropogenic microparticle pollution in surficial sediments

Anthropogenic microparticles were present throughout all 9 push-cores (Figs. 6, 7C and 7F). A total of 1255 anthropogenic microparticles were observed with optical microscopy and a

subset of the particles ($n = 13$) was verified with FTIR spectroscopy. Microfibres were the dominant anthropogenic microparticle type (microfibres = 91.3%, fragments = 5.7%, microbeads = 3.0%). Herein, the anthropogenic microparticle count quantifies as the number of particles per 50 g of dry sediment weight (particles/50 g). FTIR spectroscopy confirms 62% of the anthropogenic microparticles are plastic, with common polymers including polyvinyl butyral, polyvinylchloride, and acrylic. The remaining 38% comprise semi-synthetic polymers, including chlorinated rubber and rayon (Fig. 4; Table S3).

Microfibres in the canyon thalweg

In push-core 060 (PC060) (34 m.a.t., at the upper-transect), the grain-size range is 31-8000 μm , and the arithmetic mean gravel% and sand% are 9.6% and 90.3%, respectively; the granule-sized particles are fragmented shells (Fig. 3C; Table S1). Microfibre count in PC060 increases with sediment depth from 4 to 30 microfibres/50 g (Fig. 7C). In PC113 (0 m.a.t. at the lower-transect), the grain-size range is 2-200 μm , and the arithmetic mean sand% and silt% are 92.4% and 7.6%, respectively (Fig. 3I; Table S1). Microfibre count in PC113 decreases by 62.5% with sediment depth (Fig. 7F).

The sediment accumulation rates in BC64 (1389 m water depth, 0 m.a.t.) and BC73 (2011 m water depth, 0 m.a.t.) are 0.04 cm yr^{-1} and 1.19 cm yr^{-1} , respectively (Fig. 5E and G). Therefore, it could take 8.4-to-250 years to accumulate 10 cm of sediment in the canyon thalweg, meaning sediments containing anthropogenic microparticles in the thalweg may pre-date the mass production of plastic in the 1950's. The mobility of sediment within the thalweg can be observed in a photograph captured by the ROV ISIS during the recovery of PC060; a high level of suspended sediment is recorded in the water column of the thalweg following the passing of a turbidity current down-canyon (Fig. 8A).

Microfibres on the canyon flanks

At the upper transect, the push-cores (PC062, PC064, and PC066, located 220, 277, and 321 m.a.t., respectively) have a grain-size range of 0.25-200 μm (clay-to-fine sand) (Fig. 3D, E and F), and an arithmetic mean sand% of 54.9%, 43.8%, and 39.9%, respectively (Table S1). Microfibre count in these cores is low and uniform, ranging from 0-19/50 g with an arithmetic mean of 7/50 g (Fig. 7C). PC069 (518 m.a.t.) is located near the tributary canyons at the upper transect; the grain-size range is also 0.25-200 μm , yet despite its increased height above the central thalweg, the arithmetic mean sand% is 47.6% (Fig. 3FG; Table S1). PC069 contains the greatest range of anthropogenic microparticle types, and an arithmetic mean microfibre count of 18/50 g (Fig. 7C; Table S1). At the lower transect, PC114 and PC116, located 209 and 431 m.a.t., respectively, have the same grain-size range as the canyon flank push-cores at the upper transect, but with an arithmetic mean sand% of 17.2% and 16.5%, respectively (Fig. 3J and K; Table S1). In these push-cores, the microfibre count decreases with depth by 64.5% and 80.3%, respectively (Fig. 7F and Table S1).

The sediment accumulation rates in BC65 (1105 m water depth, 284 m.a.t.) and BC72 (788 m water depth, 601 m.a.t.) are 0.22 cm yr^{-1} and 0.09 cm yr^{-1} , respectively (Fig. 5C and I). Therefore, it could take 45-to-111 years to accumulate 10 cm of sediment on the canyon flanks and means that sediment containing anthropogenic microparticles on the canyon flanks may pre-date the mass-production of plastic.

On the canyon flanks at the upper transect, 277 m.a.t., and thus above the known thickness of the turbidity currents recorded by Heijnen *et al.* (2022), the crest orientation of sub-parallel ripples observed on the seafloor suggests a flow direction approximately perpendicular to the direction of turbidity current transport (Fig. 8B). This indicates that other

hydrodynamic processes capable of sediment transport are also active on the canyon flanks (*e.g.*, internal tides).

Discussion

Microfibre transport and burial processes

Microfibre pollution is pervasive throughout the Eastern Branch down to the 10 cm sediment depth of the push cores. Almost all push-cores show a gradual decline in microfibre concentration with depth. This gradual decline with depth is despite the marked differences in sediment accumulation rates across the canyon, and the 700% increase in the background plastic production rate. Microfibres are hypothesised to be transported to the canyon head via cross-continental shelf currents and transported through the canyon by turbidity currents (Fig. 9A and C; Chen *et al.*, 2025), and via vertical settling from marine sources (Fig. 9B and F), but their subsequent redistribution and burial cannot solely be explained by deposition from turbidity currents.

From the observed grain-size trends in the canyon thalweg (notably the absence of sediment $<31\ \mu\text{m}$ in PC060) we infer that the frequent (sub-annual) and fast (up to $5\ \text{ms}^{-1}$) turbidity currents serve to bypass and winnow silt-sized sediment and microfibres further down-canyon. Pohl *et al.* (2020) explored how the vertical distribution of microfibres was more homogeneous in turbidity currents compared to microplastic fragments. Furthermore, Chen *et al.* (2025) suggest that flushing of microfibres and other types of anthropogenic microparticles by turbidity currents in Whittard Canyon occurs due to their markedly lower settling velocity compared to quartz grains (*see* Figure 4 in Chen *et al.*, 2025). This suggests that anthropogenic microparticles are capable of being transported in the dilute, upper parts of turbidity currents,

through submarine canyons and farther into the deep sea to a wider range of depositional environments and seafloor ecosystems.

However, microfibrs were recorded at elevations up to 518 m.a.t., over an order of magnitude above the recorded thickness of measured turbidity currents. This suggests that other processes are also important in the Whittard Canyon and need be considered in other submarine canyon systems in order to develop holistic source-to-sink models for anthropogenic pollutant transfer (Fig. 9). The presence of sand in the canyon flank push-cores, and increased sand% 518 m.a.t., suggests that sediment is not sourced exclusively from hemipelagic fallout. Furthermore, this suggests that sediment, and microfibrs and other anthropogenic microparticles, stored on the Celtic Margin are being transported via episodic turbidity currents in the tributary canyons or by sediment resuspension by benthic trawling close to the canyon head and on the canyon interfluvies (Figs. 2, 3G, and 9; Table S1). The location of BC72 (Fig. 5A), high on the canyon flank opposite the Celtic Margin and the tributary canyons, could explain the low sediment accumulation rates (Fig. 5I).

The observed uniformity of the gradual decline in microfibre concentration with sediment depth suggests, however, that sub-seafloor processes also affect microfibre burial processes in the deep sea. Hyporheic transfer of microplastics has been demonstrated in riverbeds (Frei *et al.*, 2019). In sub-seafloor settings, hyporheic transfer is driven by pressure gradients, as exist between the base of turbidity currents and the seafloor (*e.g.*, Eggenhuisen and McCaffrey, 2012), and is invoked here as a control on the stratigraphic distribution of microfibrs (Fig. 9E). Internal tides have been directly monitored in Whittard Canyon (Hall *et al.*, 2017) and are observed to reflect against the steep topography of the canyon flanks in the upper canyon where they are then focused into the canyon thalweg (Amaro *et al.*, 2016; Hall *et al.*, 2017; van Haren *et al.*, 2022). This is hypothesised to cause sediment and microfibre resuspension via internal tide pumping (Fig. 9D; *e.g.*, Li *et al.*, 2019; Normandeau *et al.*, 2024).

In other submarine canyons, internal tides have been observed to rework turbidity current deposits (Normandeau *et al.*, 2024), and affect particulate organic carbon transport (Maier *et al.*, 2019). Particulate organic carbon shares similar hydrodynamic properties to anthropogenic microparticles in terms of density and irregular dimensions. On the canyon flanks of Whittard Canyon internal tide pumping may generate a sufficient pressure gradient to drive hyporheic transfer of microfibrils through sediment pore spaces, where turbidity currents are not active. Microplastic infiltration depth increases positively with sediment grain-size (Waldschläger and Schüttrumpf, 2020), hence hyporheic transfer may be enhanced in the canyon thalweg where turbidity currents and internal tide focusing are active, compared to high on the canyon flanks, where turbidity currents are absent (Fig. 9E).

Bioturbation may also play a role in controlling the vertical distribution of microfibrils in the sub-seafloor (Fig. 9E). The uppermost 10 cm of BC64 and BC65 are bioturbated (Fig. 5B and D). Sediment and microplastic mixing by bioturbation has been documented experimentally (Näkki *et al.*, 2017) and is hypothesised to occur in deep-sea sediments (Courteney-Jones *et al.*, 2020). The depth of the bioturbated layer extends to 10 cm in modern marine sediments, with individual burrows extending deeper (Tarhan *et al.*, 2015). This mixing may be enhanced on the canyon flanks due to less stressed conditions for organisms to colonize compared to the thalweg (Fig. 9E). However, a diverse suite of burrow types has been recorded in the margin of slope channel-fills where organisms can ‘shelter’ from powerful sediment gravity flows (Heard and Pickering, 2008; Hubbard *et al.*, 2012). This has the potential to further complicate sediment and microplastic mixing mechanisms in surficial submarine canyon sediments. Bioturbation and hyporheic transfer are likely important in transferring anthropogenic microparticles into pre-1950’s deep-sea sediments; the latter supported in lakes where bioturbation is absent (Dimante-Deimantovica *et al.*, 2024). The identification of a sharp, laterally continuous contact between sediments of pre-plastic production age, with an

absence of anthropogenic microparticles, and of post-plastic production age, containing anthropogenic microparticles, is required to support the formal definition of the Anthropocene. In reality, this will be challenging due to the interaction of post-depositional processes in terrestrial and deep-marine sediments.

Shredding of anthropogenic microparticle signals in the deep-sea

We suggest that sediment transport and burial processes, and anthropogenic forcing, act as nonlinear filters that can shred the environmental signal of increasing plastic production rates through time in submarine canyons. The efficiency of anthropogenic microparticle transfer from land-based sources to the Whittard Canyon is relatively low, given the land-detached nature of the canyon. This suggests that anthropogenic microparticle pollution in land-detached canyons, of which there are >5000 (Harris and Whiteway, 2011), may be dominantly marine-sourced, and that such systems receive a buffered supply of terrestrially-sourced anthropogenic microparticles. Despite this, Chen *et al.* (2025) showed that the maximum microplastic concentration per 50 g of dry sediment in Whittard Canyon was greater than that recorded in other submarine canyons. Combined with the study of Chen *et al.* (2025), the anthropogenic microparticle distribution (Fig. 7C and F) and grain-size data (Fig. 3C-K) presented here suggest anthropogenic microparticles are capable of being transported through the Whittard Canyon and are hypothesised to be transferred down-canyon to the Celtic Fan at >4500 m water depth. Given the importance of the deep sea being the ultimate sink to anthropogenic microparticles (Kane and Clare, 2019), how they are distributed in submarine fan successions and their relationship with respect to sediment depth and age should be the focus of future attempts to further understand micropollutant distribution in the deep sea. Furthermore, given

the dynamism of submarine canyons, the buffered supply of anthropogenic microparticles to land-detached canyons, and the mobility of microfibrils and thus other anthropogenic microparticles in the sub-seafloor, the efficacy of using anthropogenic microparticles as anthropogenic tracer particles is questionable, along with calculations of their fluxes.

Conclusions

By adopting a multi-disciplinary approach our results we show that anthropogenic microparticle pollution is pervasive in Whittard Canyon, at least to 10 cm sediment depth in both the thalweg, and on canyon flanks over 500 metres above the thalweg. While turbidity currents are a major agent in the transfer of anthropogenic microparticles, the turbidity currents in Whittard Canyon are only 10s of metres thick, suggesting other processes and sources of anthropogenic microparticles are needed to explain their distribution. These processes are under-represented in the stratigraphic record of deep-sea deposits and a better understanding can aid more accurate calculations of particulate matter flux. Additional sources include hemipelagic settling, and sediments on the continental shelf resuspended by benthic trawling and entering tributary canyons. Transport and resuspension of anthropogenic microparticles by internal tidal pumping likely occurs across the entire canyon water depth. Almost all the push-cores show only a gradual decline in anthropogenic microparticle concentrations down to 10 cm, despite the 700% increase in global plastic production since the 1970's. Where low sedimentation accumulation rates are recorded, much of the sediment in box-cores pre-dates plastic production. This suggests subsurface mobility of anthropogenic microparticles, with likely processes including bioturbation and hyporheic transfer. The observed distribution of anthropogenic microparticles in Whittard Canyon demonstrates they are not entirely flushed through canyons, but may be permanently or transiently stored, and be mobile within the sediment bed. These results suggest that anthropogenic microparticles incorporated in deep-

sea sediments may be a poor record of canyon particulate flux and form an imperfect timeline, meaning that identifying the Anthropocene boundary using anthropogenic microparticles in these sediments may be flawed. A multi-disciplinary approach is critical to untangling the different processes that act to transfer and bury micropollutants in deep-sea sediments, and to identifying seafloor ecosystems that are vulnerable to anthropogenic micropollutant exposure.

CRedit author contribution statement

Ed Keavney: Conceptualisation, Methodology, Formal analysis, Investigation, Writing – Original Draft, Visualisation. **Ian A. Kane:** Conceptualisation, Methodology, Resources, Writing – Review & Editing, Supervision, Project administration, Funding acquisition. **Michael A. Clare:** Conceptualisation, Resources, Writing – Review & Editing, Supervision, Project administration, Funding acquisition. **David M. Hodgson:** Conceptualisation, Writing – Review & Editing, Supervision, Project administration. **Veerle A.I. Huvenne:** Investigation, Writing – Review & Editing, Project Administration, Funding acquisition. **Esther J. Sumner:** Investigation, Writing – Review & Editing. **Jeff Peakall:** Conceptualisation, Writing – Review & Editing, Supervision. **Furu Mienis:** Investigation, Project administration, Funding acquisition. **Jonathan Kranenburg:** Methodology, Formal analysis, Visualisation.

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Figure captions

Fig. 1. Location of data used in this study. (A) Location of Whittard Canyon. (B) Location of the cores and hydrodynamic mooring in the Eastern Branch of Whittard Canyon. (C) Slope angle map of the Eastern Branch. (D) Longitudinal profile of the canyon thalweg. (E) Cross-sections through each transect (locations on B).

Fig. 2. Intensity of benthic trawling as recorded by Global Fishing Watch. (A) the Whittard Canyon 2013-2014. (B) the Whittard Canyon 2023-2024. (C) Marine Conservation Zone (MCZ) 2013-2014. (D) Marine Conservation Zone (2023-2024).

Fig. 3. (A) Cross-section of the samples for grain-size analysis. Grain-size distribution plots for the sediment trap at the M1 mooring site of Heijnen *et al.* (2022) (B) and the push-cores of the current study (C-K).

Fig. 4. Micro-Fourier transform infrared (μ -FTIR) spectroscopy spectra and microscope photographs of microfibrils. (A) Rayon μ -FTIR spectra. (B) Polyester μ -FTIR spectra. (C) Polyethylene μ -FTIR spectra. (D) Polystyrene μ -FTIR spectra. (E) Chlorinated rubber μ -FTIR

spectra. (F) Polypropylene μ -FTIR spectra. (G) Photograph of polyester microfibre. (H) Photograph of rayon microfibre.

Fig. 5. (A) Cross-section showing location of the box-cores used in ^{210}Pb dating. (B-I) Core photographs and sediment accumulation rate plots for the box-cores. (B and C) Box-core 65. (D and E) Box-core 64. (F and G) Box-core 73. (H and I) Box-core 72. m.a.t. is metres above thalweg.

Fig. 6. Box plot for microfibre concentration and sediment depth for all push-cores.

Fig. 7. Anthropogenic microparticle count with sediment depth for the push-cores located in Whittard Canyon. (A, B, D, and E) Location maps and high-resolution bathymetric maps of the Eastern Branch. 3X vertical exaggeration. (C and F) Anthropogenic microparticle trends for each push-core. (G) Cross-section of the Whittard Canyon showing the push-core locations. In PC060, the 1950 plastic production onset is based on the sediment accumulation rate calculated from ^{210}Pb dating of the sediments in Box-core 64. The sediment accumulation rate calculated from BC65 can be approximately tied to PC064 and equates to 16.5 cm of sediment accumulation in the 75-year period since the onset of plastic production. The push-cores and box-cores are not co-located within Whittard Canyon, but based on their longitudinal position and height above the thalweg, they are deemed suitable for relating sediment accumulation rate to the presence of anthropogenic microparticles with depth.

Fig. 8. Photographs taken of seabed push-core sampling from the Remotely Operated Vehicle. (A) Canyon thalweg at the upper-transect. (B) Canyon flanks at the upper-transect.

Fig. 9. Synthesis of microfibre transport and burial processes in submarine canyons. (A-D) Transport processes. (E) Sub-seafloor processes. (F) Anthropogenic forces. Part C is modified from Chen *et al.* (2025).

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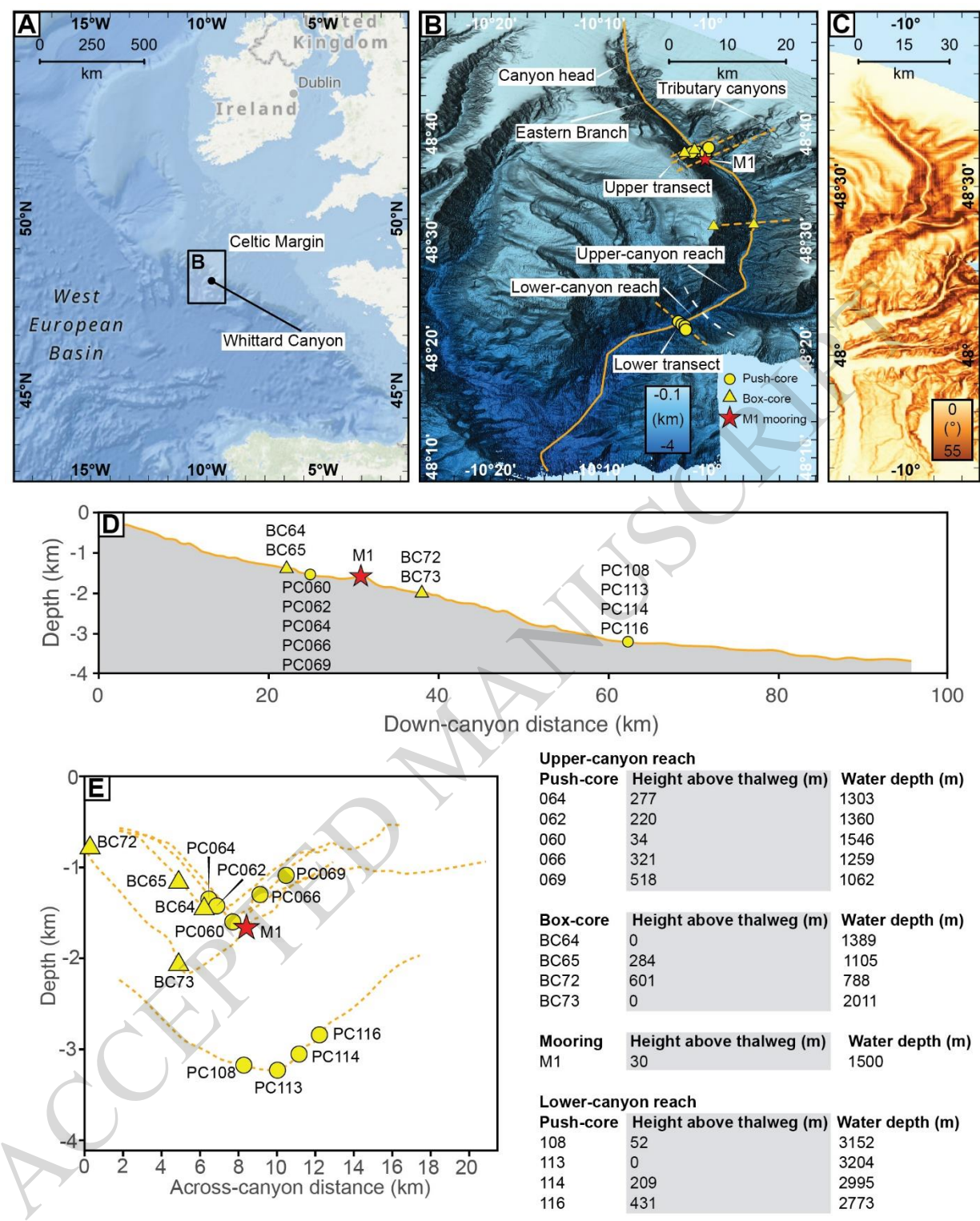


Fig. 1

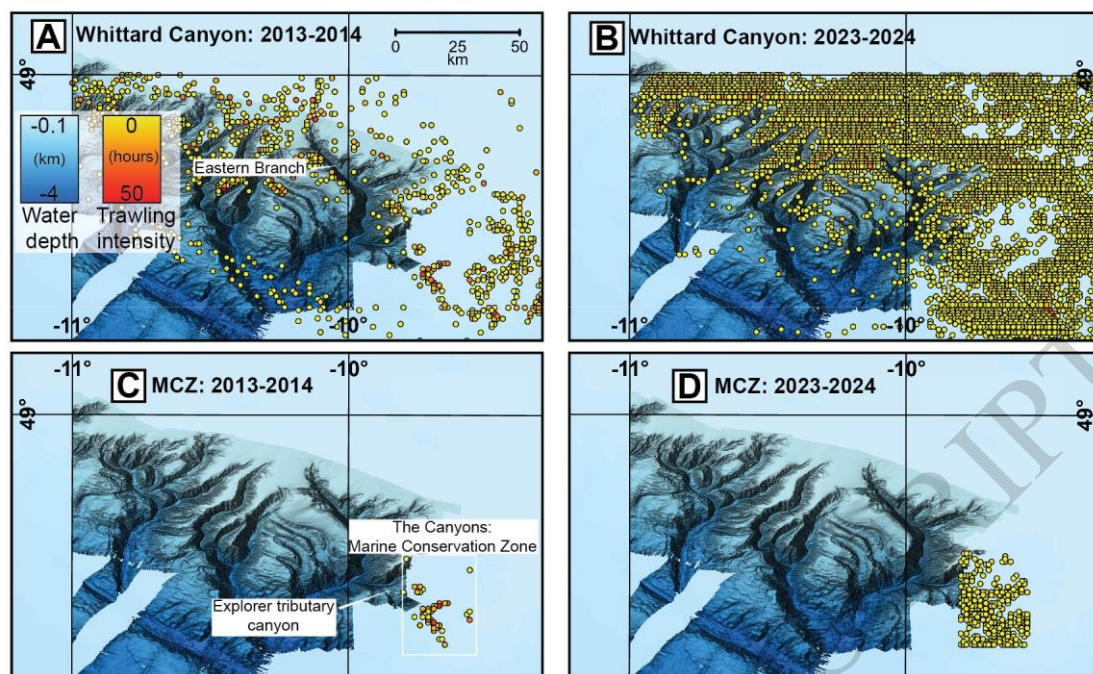


Fig. 2

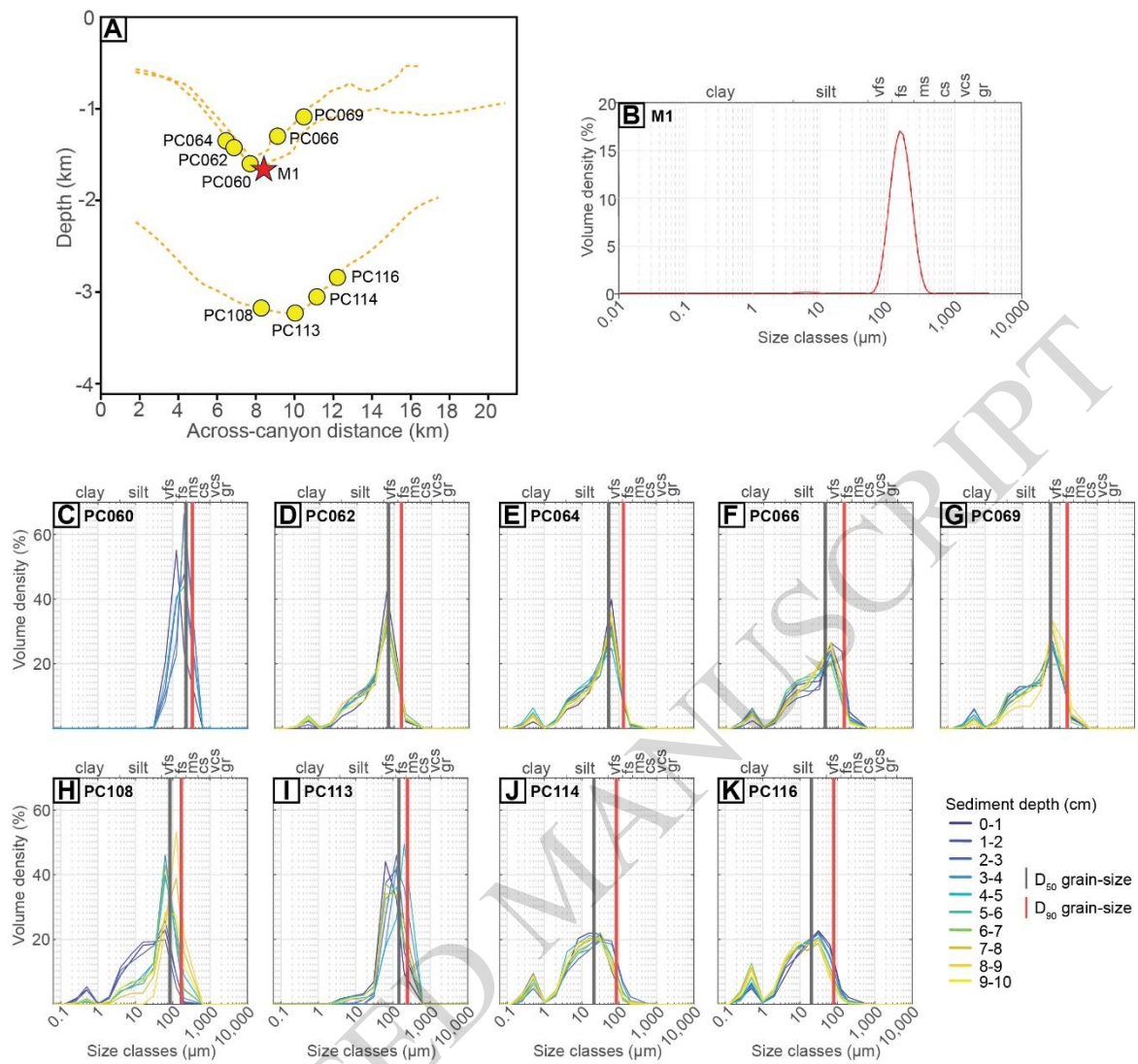


Fig. 3

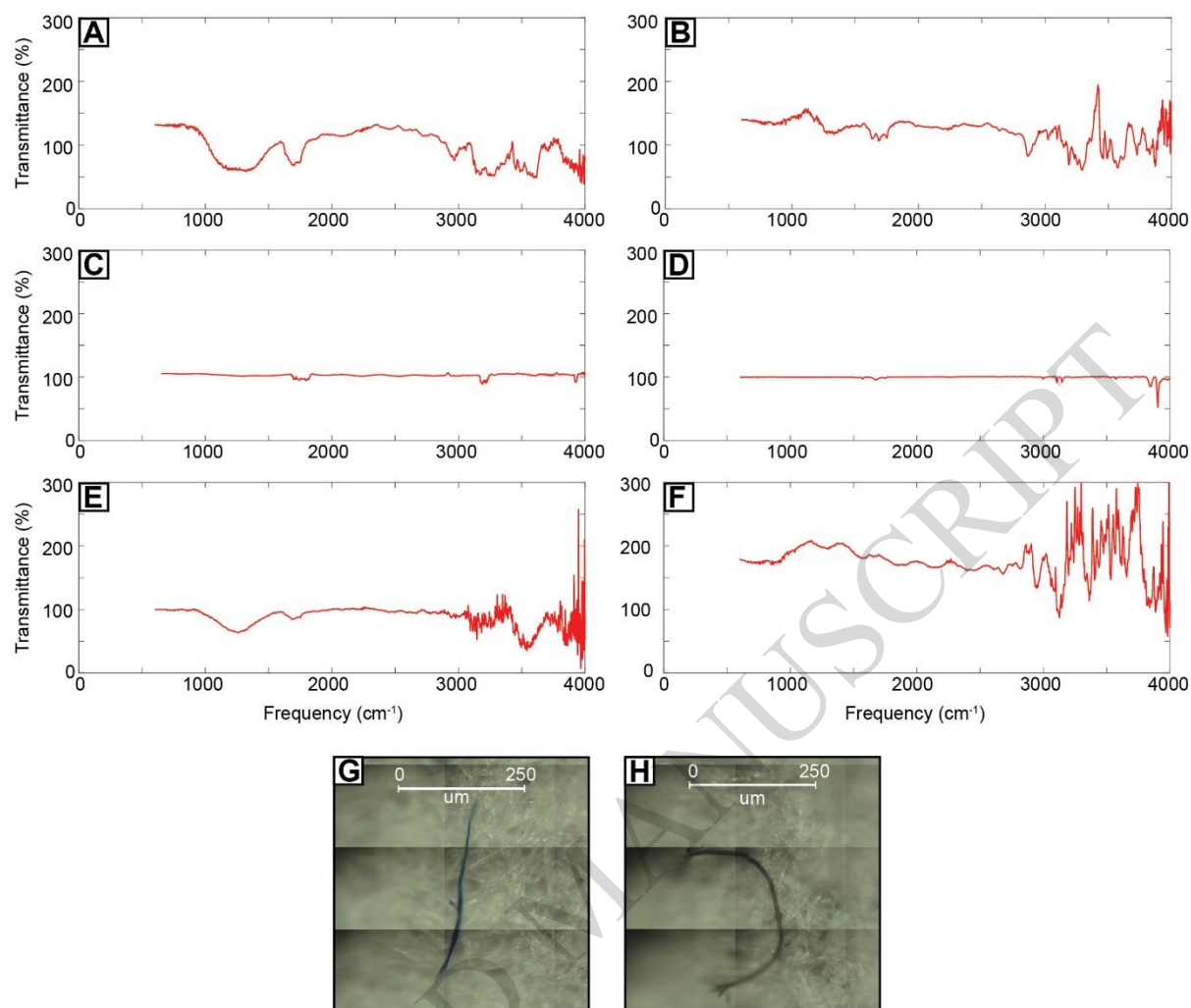


Fig. 4

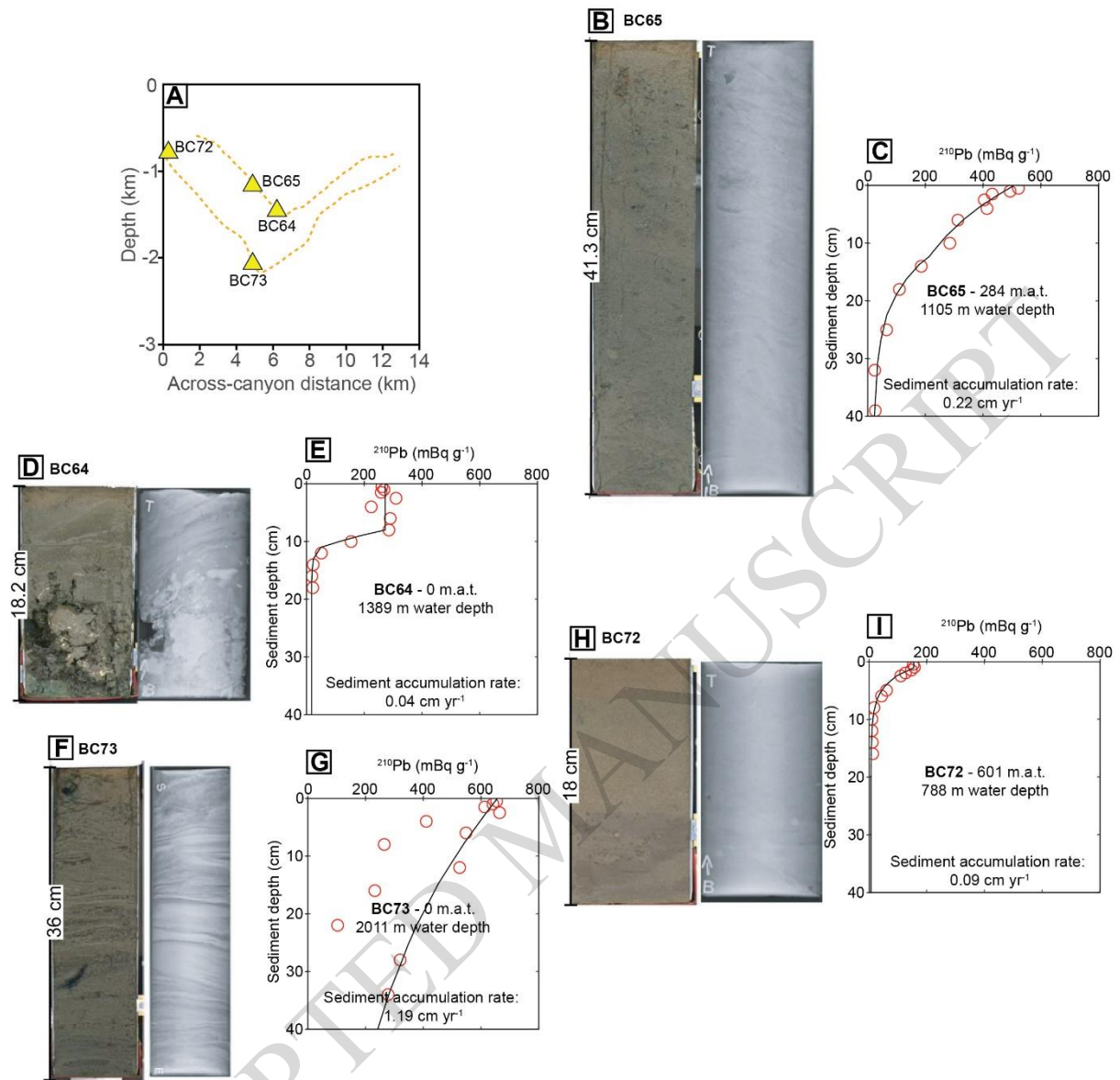


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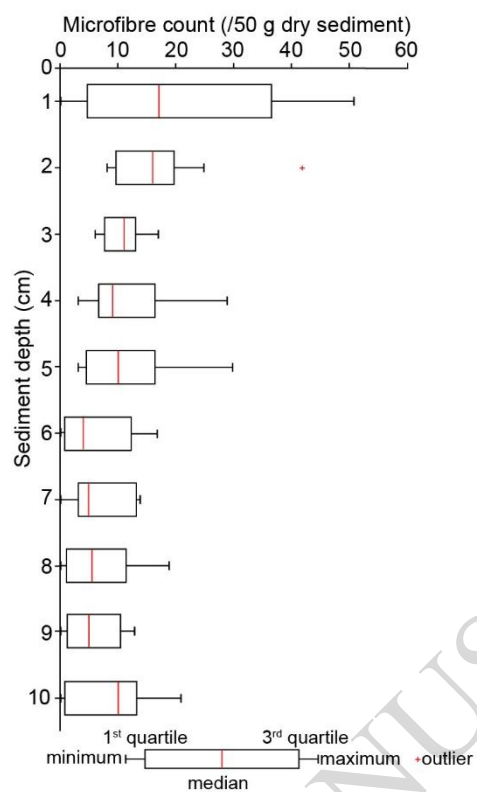


Fig. 6

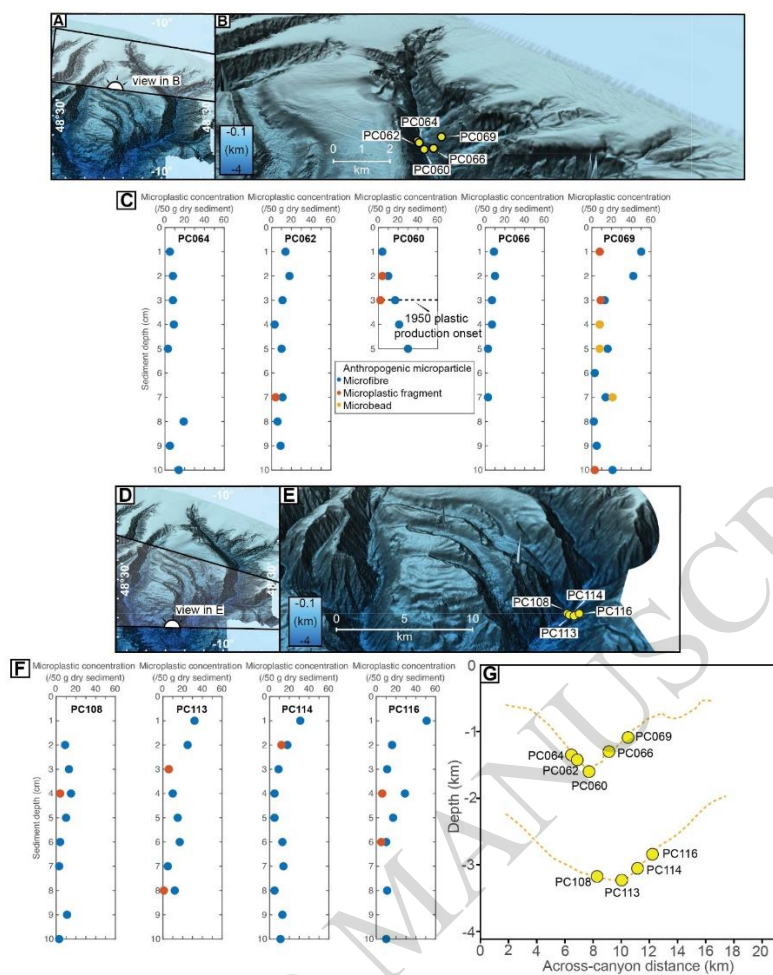


Fig. 7

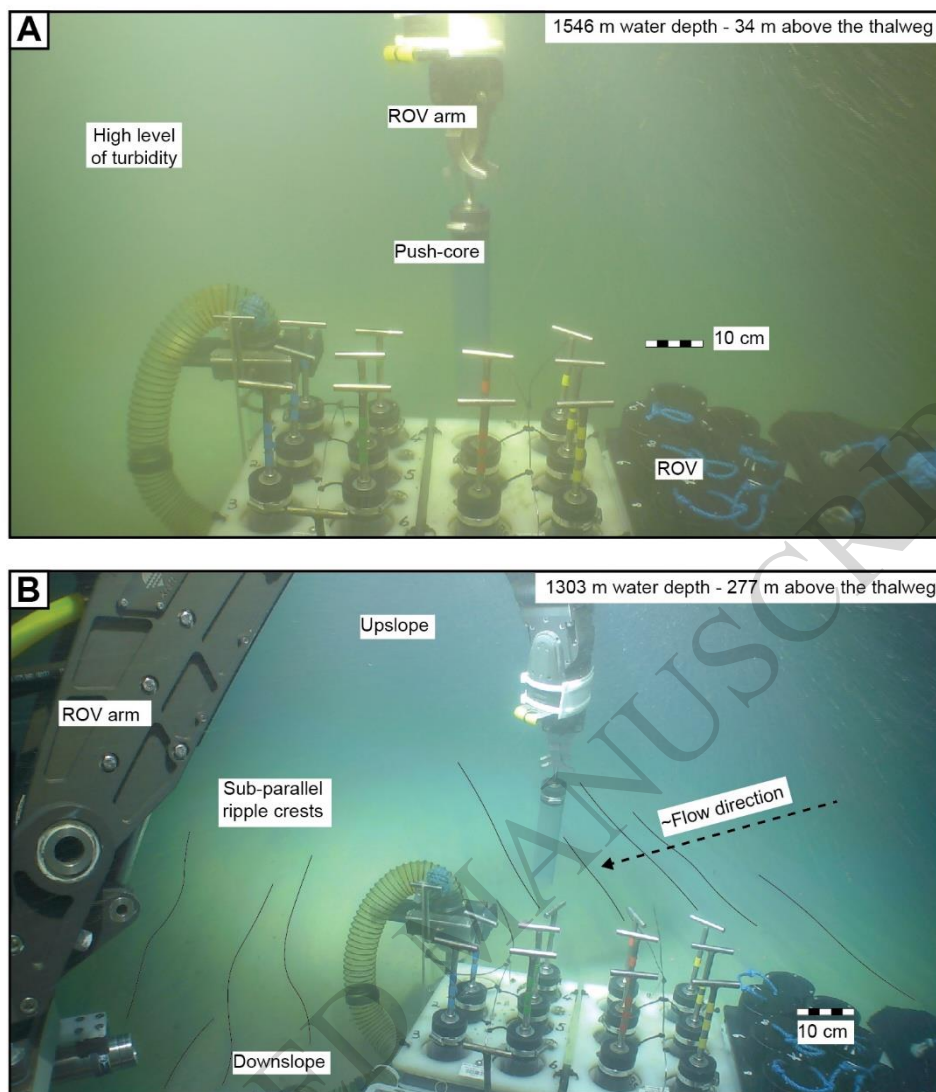


Fig. 8

Transport processes

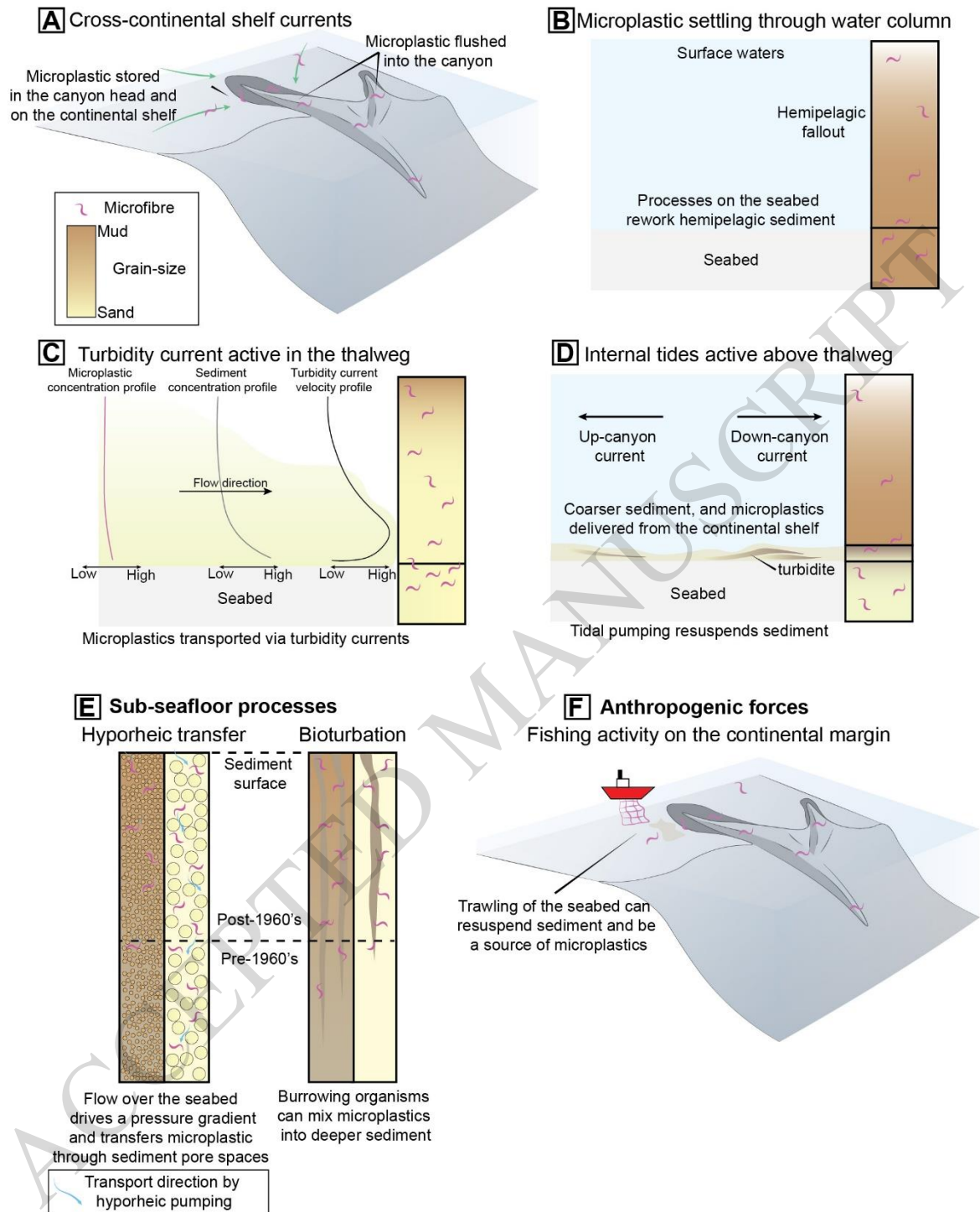


Fig. 9