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Microplastic pollution distribution: Differences between marine reserves and urbanised areas

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A B S T R A C T

Microplastic particles (<5 mm) have been observed to be widely distributed in the oceans, from estuaries the deep ocean trenches. While plastic pollution in the marine environment is a growing concern worldwide, relatively little is known about microplastic distribution and accumulation on the seafloor, particularly in marine protected area (MPAs). The delimitation of MPAs frequently follow jurisdictional or political boundaries, however the distribution of species, habitats and ecosystems does not always follow these same confines. Likewise, pollution in the marine environment do not have boundaries.

This study compares microplastic content in sediment cores from two sites: an urbanised area, near the coastal township of Picton; and a site distal from the township (~30 km) but proximal to open ocean, adjacent to the Kokomohua Marine Reserve, in the region of Queen Charlotte Sound/Tōtaranui (QCS), Aotearoa/New Zealand.

Microplastic particles were identified throughout the sediment cores from both locations, reaching depths of ~45 cm below the seabed. Our findings revealed that marine sediments adjacent to the marine reserve had four times the microplastic accumulation of marine sediments from near the coastal township. The abundance of microplastics across the sediment depth profiles also varied between the two sites, suggesting different accumulation of microplastics on the seafloor due to differences in the frequency and extent of seabed disturbance experienced by the two locations.

Our study demonstrates the extent to which human stressors such as microplastic pollution proliferate and concentrate in the environment, particularly in areas considered to be near-pristine with strict environmental protections.

1. Introduction

1.1. Microplastic pollution in the marine environment

Microplastic particles (<5 mm) waste has reached planetary-scale exposure, with 710 million tons of plastic waste estimated to enter the world's marine environment by 2040 (Jambeck et al., 2015; Lau et al., 2020). Calculations have shown that at least 5.25 trillion microplastic particles are currently floating in the global ocean, and up to 90% of these can remain suspended in the water column, become trapped along the coast or ultimately settle and accumulate within marine sediment (Eriksen et al., 2014; Harris et al., 2021, 2023), with poorly understood disruptive impacts on vital Earth system processes (Arp et al., 2021).

Microplastics enter the ocean as micro-sized particles or degrade to micro-sized particles from larger plastic fragments (Andrady, 2011; Gregory and Andrady, 2003; Thompson, 2015). There are terrestrial and aquatic sources of microplastics, including sewage and wastewater systems, riverine inputs, aquaculture and fishing activities (Browne et al., 2011). Once in the ocean, light and highly mobile microplastic particles behave like any other sediment particles, being transported by ocean currents (e.g., gravity flows, bottom currents) and accumulating on and below the seafloor, considered the global sink for plastic particles (Baudena et al., 2023; Dong et al., 2018; Eriksen et al., 2014; Harris, 2020; Kane et al., 2020; Kane and Fildani, 2021; Martin et al., 2022). Thus, microplastics ultimately become part of the sedimentary record (Harris, 2020; Kane and Clare, 2019), with some scientist even referring

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to this geological period of time as the 'Plasticene' (Haram et al., 2020). On top of natural dynamic processes (e.g., near-bottom currents) controlling particle transport in the ocean, human activities in the marine environment (e.g., bottom trawling, dredging or anchoring) can cause sediment resuspension, altering the sediment deposits and accumulation rates (Amoroso et al., 2018; Handley et al., 2014; O'Neill and Ivanović, 2016; Oberle et al., 2016; Paradis et al., 2021), and therefore also influence distribution and settlement rates of microplastics. Microplastic particles are detected in marine sediments across all ocean depths at more than 800 locations worldwide (e.g., Chiba et al. (2018); Jamieson et al. (2019); Kane et al. (2020), among others), although most studies (80%) have been conducted in Europe and Asia (Phuong et al., 2021). In Aotearoa/New Zealand, the presence of microplastic particles on beaches was reported for the first time in 1977 (Gregory, 1977; 1978), but microplastic pollution did not attract scientific or societal attention until recent years (Ladewig et al., 2021; *Plastics in the Environment*; *Rethinking Plastics in Aotearoa New Zealand. Royal Society Te Aparangi, 2019*). In the last decade, microplastics have been identified in rivers, and coastal and intertidal zones around New Zealand (Bridson et al., 2020; Dikareva and Simon, 2019; Ladewig et al., 2023; Tremblay et al., 2019). Even still, there is limited knowledge about where and how fast microplastics are accumulating in marine environments around New Zealand, particularly in the subtidal zone.

Microplastic have known impacts on benthic communities and microbial functions, such as carbon sequestration (Ladewig et al., 2021; Underwood et al., 1995). Yet, many questions remain concerning the effect of microplastics on important marine ecosystem functions. For example, microplastic particles have been shown to affect the ability of microbes to process carbon and other nutrients (Seeley et al., 2020), sometimes leading to heavy metal build up or even genetic shifts such as the upregulation of antibiotic resistance (Chamas et al., 2020). Similarly, filter-feeders such as mussels, are highly vulnerable to the ingestion of microplastics, which can then be transferred along the food chain with potential risks for human health (Barboza et al., 2018; Chamas et al., 2020; Huang et al., 2021; Ugwu et al., 2021). Sediment systems within areas like marine reserves are typically considered efficient carbon sinks due to reduced disturbance by human activities and more efficient burial rates (Laffoley et al., 2019; Roberts et al., 2017; Sala et al., 2021) – the degree to which coupled microplastic burial may impact this deserves further attention.

To understand the role of sedimentary and biological processes in determining the fate of plastic particles in the marine environment we must first quantify microplastic particle accumulation and distribution in marine sediment across a range of locations. In this study we hypothesise that: 1) the concentration of microplastics will decrease with distance from urbanised coastal areas, and with depth below the seabed; and 2) the types of microplastics will be different at each site, possibly relating to differing input sources of plastic. This study represents the critical first step towards determining the concentration and distribution of microplastic in New Zealand's marine environment. This knowledge will help to inform policies to mitigate microplastic pollution, crucial for marine pollution management in coastal areas and marine protected areas (MPAs) – regions with social, cultural, and economic importance.

1.2. Regional settings

Located in the Marlborough Sounds, north of the South Island of New Zealand, the Queen Charlotte Sound/Tōtaranui (QCS) covers an area of ~4000 km^2 with depths ranging from the coast to ~350 m at the opening to the Cook Strait (Fig. 1). The coastal town of Picton is at the head of QCS, and ~5.5 km seaward is located the Picton Anchorage, at ~35m water depth (Fig. 1). This area has a tidal range of ~1.5 m and is protected from strong currents and swell waves (Hadfield et al., 2014; Ribó et al., 2021). Picton is the gateway to the South Island, with high vessel traffic transporting passengers and goods between New Zealand's North and South Islands. Albeit a small township, the region is known for forestry, aquaculture, and tourism. Recent research conducted in this area shows that high-tonnage vessel anchors regularly excavate the seafloor up to 80 cm in the Picton Anchorage area, and individual ships in this area can displace up to 2800 m^3 of seabed sediment (Watson et al., 2022).

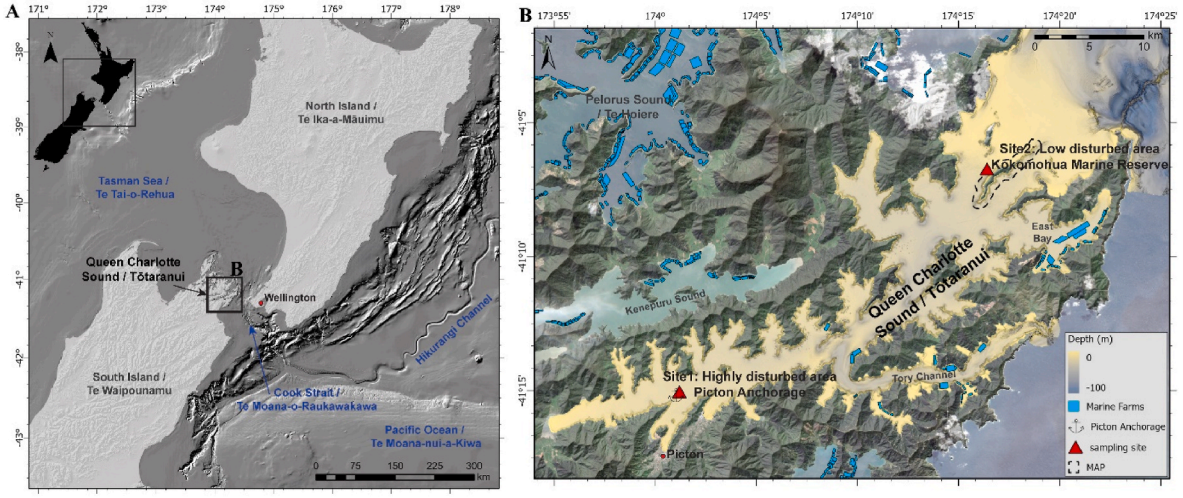

Fig. 1. A) Regional setting of the Queen Charlotte Sound/Tōtaranui (QCS), in the Marlborough Sounds region, north of the South Island of Aotearoa/New Zealand. Bathymetric map of QCS showing the location of the marine farms in the region (blue polygons), and the sampling sites (red triangles) at Picton Anchorage (site 1) and Marine Reserve Long Island – Kokomohua (site 2). Black dashed line delineated the Marine Protected Area (MPA). Background satellite image Sentinel-2 and lidar (8-m digital elevation model) obtained from Land Information New Zealand (LINZ). All figures were constructed using ArcGIS PRO version 2.9.0 and Adobe Illustrator 2022.

At the entrance of QCS, the Kokomohua Marine Reserve (also known as Long Island) covers an area of ~6 km^2 and (Fig. 1), and was formally established on April 1993 (Davidson et al., 2014; Marine Reserve Long Island-Kokomohua. Order 1993). This Marine Reserve is exposed to the Cook Strait wave regime and storm events, and includes Long Island, the sub-tidally connected Kokomohua islands and an unnamed charted rock to the north-east, extending ~6.5 km in length and ~463 m offshore from the charted rock and from the high-water mark around the islands (Fig. 1).

The Marlborough Sounds region has been impacted by cumulative stressors since the 1800s, including overfishing and overexploitation (e.g., scallop beds), seabed disturbance (e.g., bottom trawling, dredging, anchoring practices), and increased terrigenous sedimentation loads into the Sounds (e.g., land run-off due to the steep slopes of the mountains surrounding the Sounds, land clearing, logging, etc.) (Urlich and Handley, 2020). Nonetheless, the Marlborough Sounds produces over 80% of the New Zealand's aquaculture exports (Aquaculture Strategy, The New Zealand Government Report (2109)), with the majority of the marine farms located in Pelorus Sound/Te Hoiere, and only a few found in East Bay, in the QCS area (Fig. 1).

The seabed substrate in the QCS area is predominantly fine sediment (i.e., silt and clay fraction), but larger sand fraction to gravel sized particles are also observed towards the higher energy regions near the opening to Cook Strait (Ribó et al., 2021; Watson et al., 2020). With the absence of large rivers there are no significant freshwater (and sediment) inputs in this area (Heath, 1974). The fine sediment is mostly derived from large land run-off and the increased seabed disturbance due to human activities, such as trawling, dredging and high-tonnage ships anchoring (Handley, 2016; Urlich and Handley, 2020; Watson et al., 2022).

2. Material and methods

2.1. Sediment sampling

Sediment core samples were collected from two sites in QCS during the IKA2004 survey on board the RV *Ikatere* in July 2020. Sampling site 1 was located in an area with large human impacts near the Picton Anchorage, at ~35 m water depth. Sampling site 2 targeted an area with relatively low-human impacts, ~30 km from the Picton township, ~700 m to the west of the Kokomohua Marine Reserve, at ~24 m water depth (see Fig. 1 for sampling sites location).

The replicate sediment cores of between 20 cm and ~70 cm length (n = 4 at each site), were collected using a four tube (diameter ø 100 mm) KC Denmark Multicorer (KC Denmark Multi-Corer Manual). The allocated set of analyses for this study was: *a)* microplastic (site 1: 40 cm long, site 2: 46 cm long), *b)* colloidal extracellular polymeric substance-carbohydrate (EPS, site 1: 37 cm long, site 2: 22 cm long), *c)* particle size distribution (site 1: 41.5 cm long, site 2: 21 cm long), d) sedimentological analyses (site 1: 36 cm long, site 2:71).

At least one specialised non-plastic Cellulose Acetate Butyrate (CAB) core liner was used in one of the four tube KC Denmark Multicorer in each sampling site. This CAB tube was used to collect sediment samples for the microplastic analyses, to avoid plastic contamination and to ensure a known composition of the core tube material during sampling acquisition.

2.2. Laboratory methods

2.2.1. Microplastic analyses

The CAB sediment cores were carefully split opened in the University of Auckland laboratory, avoiding CAB contamination into the sediment. The sediment cores were sub-sampled every 2.5 cm for the first 10 cm (each sample with a volume of 88 cm^3), and every 5 cm from the 10th cm downcore to the end of the core (each sample with a volume of 176 cm^3).

A density separation process using NaI solution was applied to separate the microplastic particles from the sediment grains (see details in Supplementary Material). The resulting supernatant containing plastic particles was filtrated in a fibre glass filter (pore size 0.45 μm).

The filters were examined under microscope (× 4 magnification) and microplastic particles were identified and quantified using a visual identification technique following Frias et al. (2018), based on the physical properties (i.e., size, shape, type, colour) of the particles.

Chemical analysis of sediment samples at shallow (0–5 cm), middle (10–15 cm) and deep (35–40 cm) depths in the two sampling sites were conducted using Confocal Raman spectroscopy to identify the polymer types. Raman spectra were acquired in backscattering geometry using a LabRAM HR Evolution Raman confocal microscope. The excitation radiation used was a 532 nm solid state laser, focused with a x100 objective (NA 0.90). A 600 gr/mm (500 nm) blazed grating was used in combination with a holographic filter to remove Rayleigh scattered light. Signal was captured with a CCD detector with the confocal pinhole set to 1000 μm to increase signal intensity. The laser was tightly focused on individual particles with laser powers and acquisition time varied to maximise the signal while not degrading the sample. Visible as well as spectral changes were used to monitor degradation. Spectral analysis was performed using LabSpec 6 software (HORIBA Scientific (*LabSpec 6 Spectroscopy Suite Software Manual*).

2.2.2. Colloidal extracellular polymeric substance-carbohydrate (EPS) analysis

Sediment cores were subsampled (approximately 200 mg) and frozen to −80 °C for analysis of EPS. Sediment was lyophilised and colloidal carbohydrate was extracted following Underwood et al. (1995), and quantified using the phenol-sulphuric Dubois assay (Dubois et al., 1956) and spectrophotometry (Mettler Toledo UV5 UV/Vis spectrophotometer). The 485 nm absorbance value was converted to colloidal carbohydrate concentration of μg glucose equivalents ml^{-1} using calibration standards and converted to mass of glucose equivalents per mass of dry sediment (μg/g).

2.2.3. Sedimentology and sediment particle size analysis

Sediment cores used for the microplastic analyses were first logged visually in the field and then analysed ashore using X-ray Computed Tomography (CT) scan conducted on the Pacific Radiology (Lower Hutt) CT scanner. The CT scanner was set to 120 kV, 250 mA and pitch of 0.625 mm, and the CT data was processed in the software ImageJ to produce sagittal slice images, which were used to build the sedimentology graph logs.

Sediment cores for grain size distribution analyses were subsampled onboard in slices of 1 cm thick and also frozen to −80 °C upon return to the laboratory. Sediment subsamples were lyophilised and immersed in distilled water for 24h to remove saline content and digested in hydrogen peroxide (20–30%) to eliminate any organic matter content. Particle size distributions were measured using laser diffraction (Malvern Mastersize, 2000 particle sizer).

3. Results

3.1. Microplastic particles in Queen Charlotte sound marine sediments: concentration and distribution

Microplastics were detected throughout the sediment cores at both sampled sites, down to depths ~46 cm below the seabed (i.e., maximum depth examined in this study). A wide range of type, shapes, size and colour of microplastic particles were identified throughout both sediment cores (Fig. 2). The most common microplastics found are the light blue and white fragments (see example in Fig. 2B and D) and black and dark blue fibres (Fig. 2A and C).

The sediment sample collected at site 1, near the coastal township of Picton, shows a near-homogeneous vertical distribution of microplastic particle concentration, ranging from between 0.02 and 0.09 plastic particles/cm^3 of volume sample throughout the sediment core (Fig. 3A). The top 5 cm hosted only 0.11 particles/cm^3 (i.e., 10 particles in the sediment sample, Fig. 3A), which is four times less than the microplastic accumulated in the surface sediment at site 2 near the marine reserve (i.e., 0.45 particles/cm^3, 40 plastic particles in the top 5 cm of the sediment sample, Fig. 3B).

The greatest abundance of microplastics was identified within the top 5 cm of the sediment core collected at site 2, adjacent to the Kokomohua Marine Reserve, with 0.25 particles/cm^3 (Fig. 3B). The lowest abundance was also detected in this sediment core, at depths of 10–15 cm below the seafloor, with only 0.005 particles/cm^3 (i.e., 1 particle in the sediment sample; Fig. 3B). In addition, our results show a peak of microplastic particles concentration at this site, at a depth of 40 cm below the surface (Fig. 3B). We quantified 0.1 particles/cm^3 (i.e., 17 particles in the sediment sample between 35 and 40 cm; Fig. 3B), which is the same magnitude of microplastics concentration as at the seafloor surface in this core.

3.2. Types of microplastics accumulating in Queen Charlotte sound marine sediments

Raman spectroscopy identified seven polymer types across both sites (Fig. 4; Table 1). The most common polymer types observed are Polytetrafluoroethylene (PTFE) (38%), Polypropylene (PP) (29%) and Polyethylene terephthalate (PET) (18%).

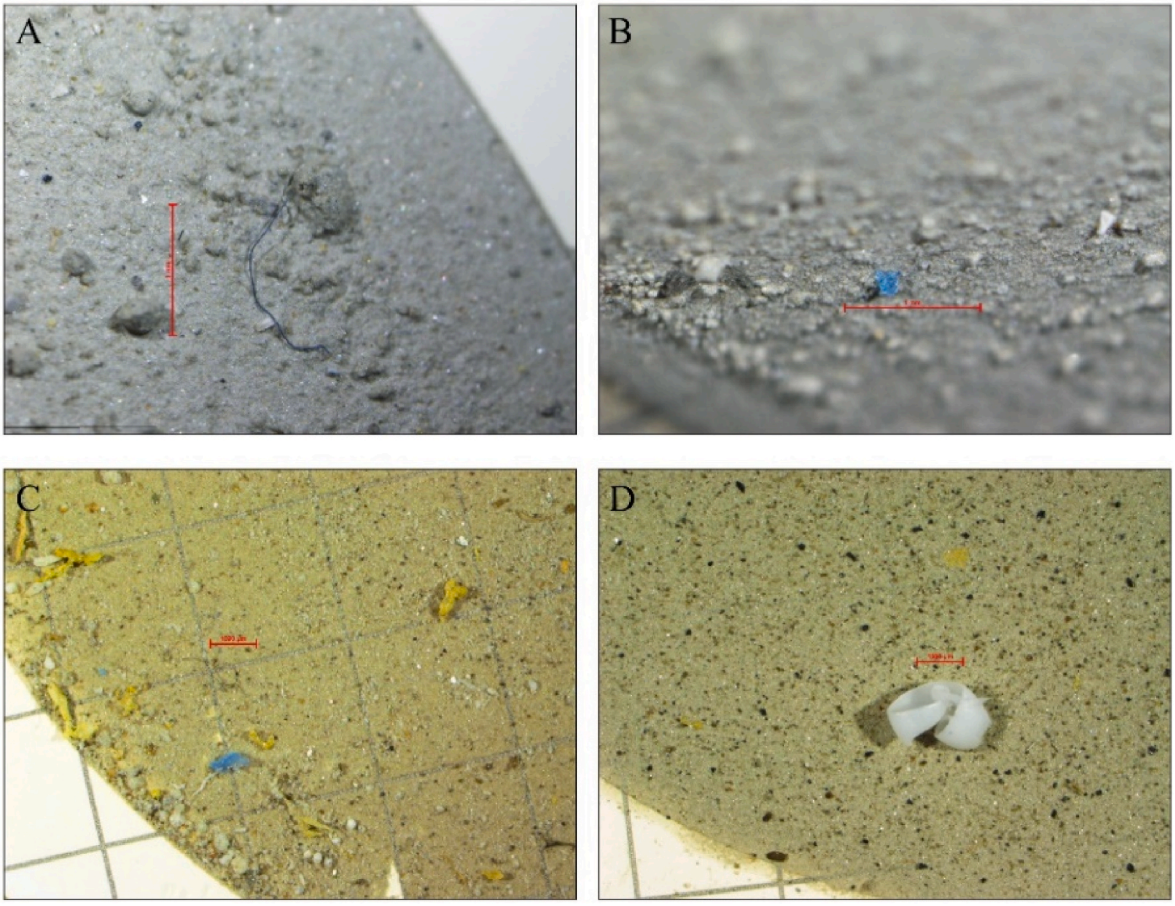

Fig. 2. Microplastic particles observed during the microscopic visual identification (red line indicates 1 mm scale bar). **A)** Dark blue fibre identified at 0–2.5 cm core depth, and **B)** Light blue particle detected at 20–25 cm core depth; both from the sediment core collected in site 1, Picton Anchorage. **C)** Light blue particles and black fibre found at 0–2.5 cm core depth, and **D)** white pellet found at 35–40 cm core depth; both examples from the sediment core collected in site 2, adjacent to Kokomohua Marine Reserve (see location in Fig. 1).

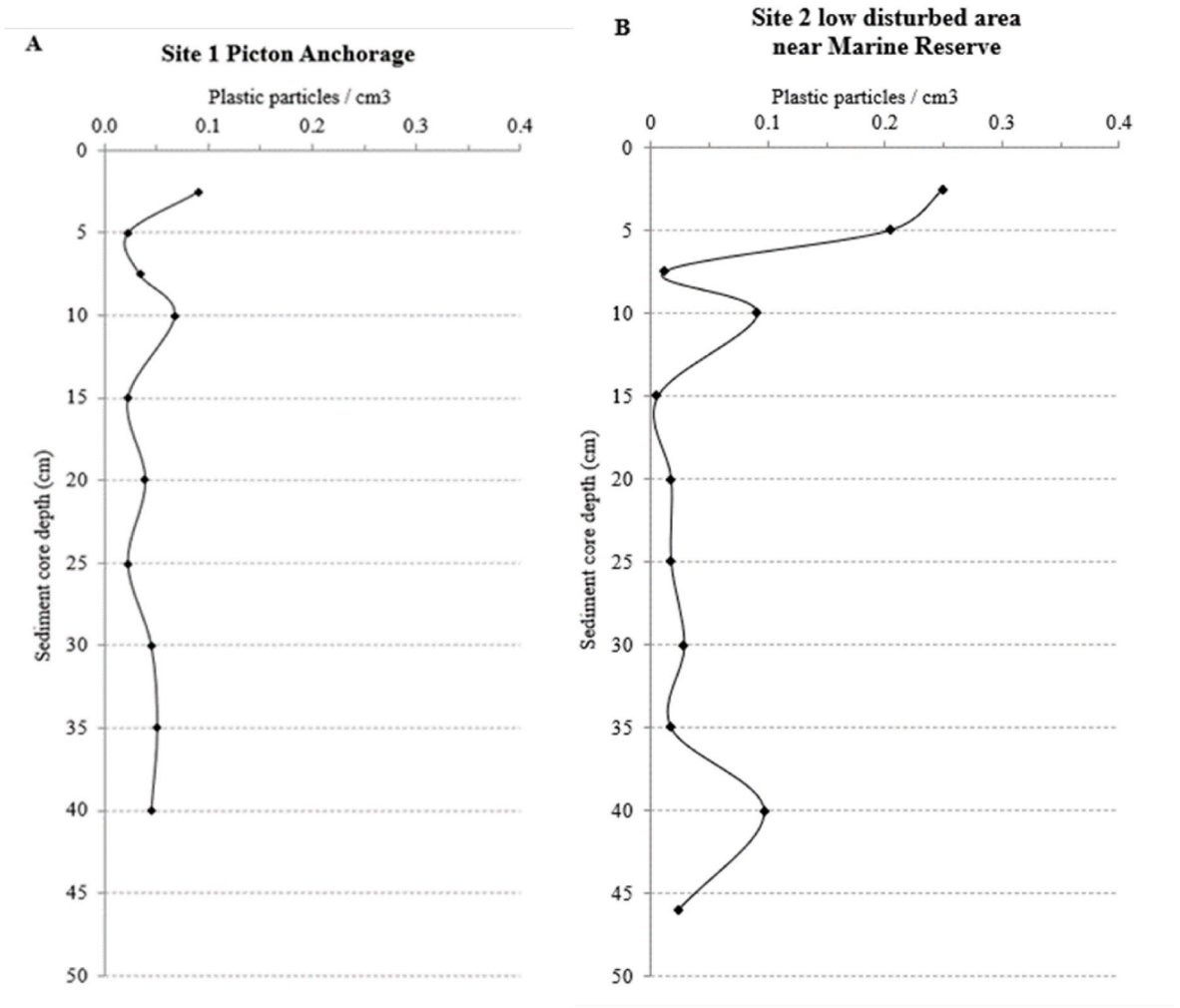

Fig. 3. Microplastic particles abundance at each depth interval averaged across the sediment cores collected in **A)** site 1, Picton Anchorage (Std Dev $\sigma = 0.02$); and **B)** site 2, adjacent to Kokomohua Marine Reserve (Std Dev $\sigma = 0.08$) (see location in Fig. 1; for tabulated data points see Table S1).

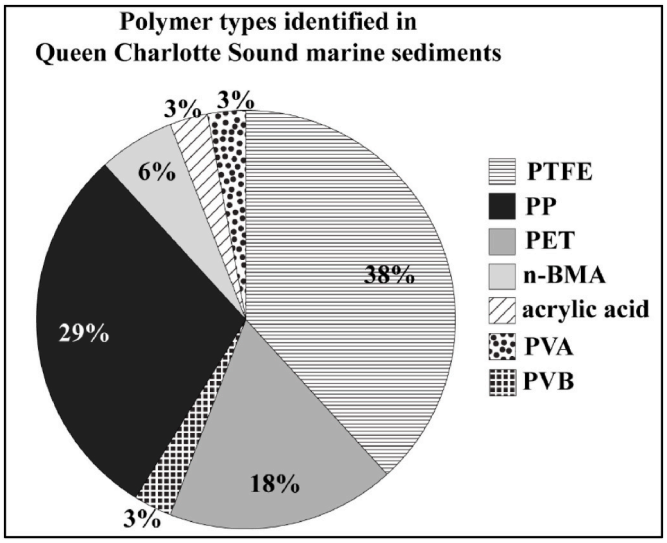

Fig. 4. Diagram showing the percentage of the different polymer types identified in the Queen Charlotte Sound Tōtaranui (QCS) marine sediments (see full names of polymers in Table 1).

An example of the three most prevalent microplastics identified and their corresponding spectra are shown in Fig. 5.

While we detected different concentrations of microplastics (Fig. 3) and polymer types (Fig. 4; Table 1) between the sites, it is important to note that the number of particles that were successfully analysed using Raman Spectroscopy differed substantially between the sites. Much lower number of particles were analysed at site 1, Picton Anchorage (8.5%) than at site 2, the Kokomahua Marine Reserve (34%, Table 1). Not all microplastic particles or fibres in the samples at this site were identifiable (i.e., distinguish polymer type) using Raman spectroscopy for two reasons: i) overwhelming fluorescence observed in some of the red fibres which masked the Raman signal, and ii) only Raman signals from pigments in the polymer were detected in some of the blue fibres/particles due the high Raman response of those molecules compared to the polymer Raman response.

In order of concentration from highest to lowest, the Picton Anchorage (site 1) was characterised by equal portions of PP and poly-n-Butyl Methacrylate (n-BMA) and by PTFE. Polymer type n-BMA was only present in the Picton Anchorage (site 1). The Kokomahua Marine Reserve (site 2) was characterised by PTFE, PP, PET, and equal parts Polyvinyl acetate (PVA), Polyvinyl butyral (PVB) and acrylic acid. At this site, we found very high prevalence of PTFE white particles. This

Table 1
Polymer types identified in the marine sediments in Queen Charlotte Sound/Tōtaranui.

Polymer type	Site 1 Picton Anchorage	Site 2 Kokomohua Marine Reserve
Polytetrafluoroethylene (PTFE)	1	12
Polyethylene terephthalate (PET)		6
Polyvinyl butyral (PVB)		1
Polypropylene (PP)	2	8
poly-(n-Butyl Methacrylate) (n-BMA)	2	
acrylic acid		1
Polyvinyl acetate (PVA)		1
Total polymers identified	5	29
Total microplastic particles detected (see details in Table S1)	59	85
Proportion of polymers identified	8.5%	34%

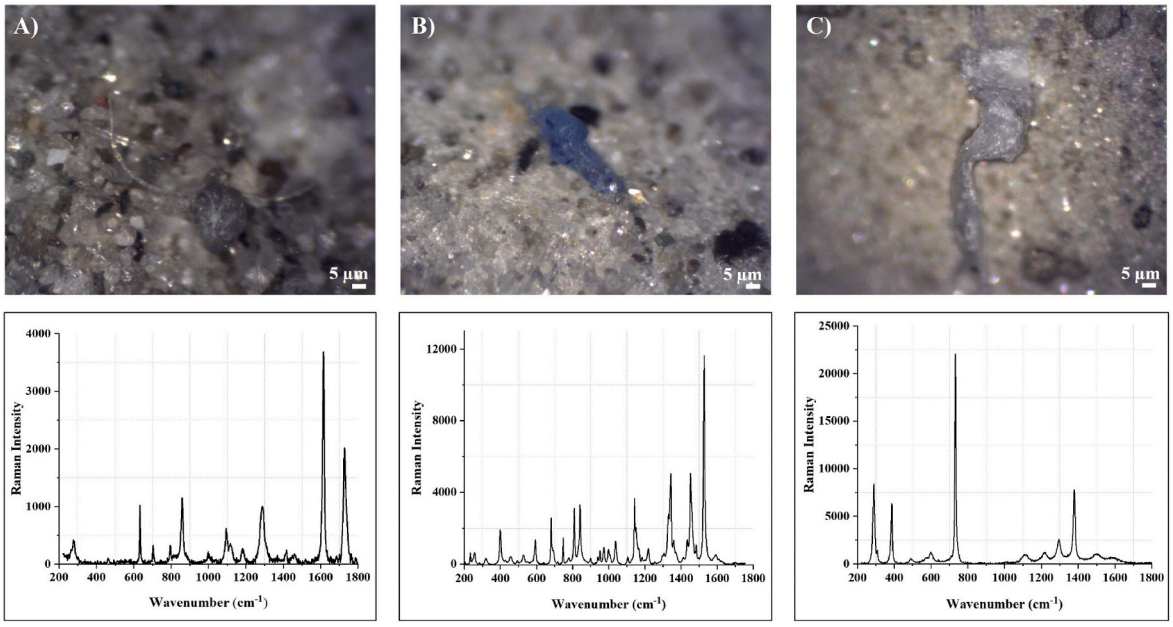

Fig. 5. Microplastic particles images and their corresponding Raman spectra for **A)** PET fibre collected at site 2 (adjacent to Kokomohua Marine Reserve) at 0–5 m depth; and **B)** PP particle collected at site 2 (adjacent to Kokomohua Marine Reserve) at 0–5 m depth (Raman spectra (intensity) showing combination of PP and blue pigment signals) and **C)** PTFE microplastic collected at site 1 (Picton Anchorage) at 35–40 m depth.

polymer was detected at all depths, however, the majority (80%) of PTFE particles were detected between 35 and 40 cm depth. PP showed a similar trend in distribution as PTFE particles at this site (i.e., detected throughout all depths, with maximum presence at 35–40 cm depth). Small PP particles (size >100 μm) were observed at depth (35–40 cm) compared to the particle size observed at the surface (0–5 cm) sediment layers (>500 μm). On the contrary, the distribution of PET microplastics at this same site near the Kokomohua Marine reserve (site 1) did not follow this same trend. Instead, higher number of particles were observed at 10–15 cm depth. Additionally, Polymers PVA and acrylic acid were detected at the surface between 0 and 2.5 cm, and also at 35–40 cm depth.

3.3. Sediment characteristics

Bottom sediments on both sites have dominant silt (up to ~70–90%) and a small portion (~1–7%) of clay. Site 1 is characterised by dominant fine fraction (i.e., poorly sorted fine silt), with very low content of sand (~3%) mainly throughout the entire core (Figs. 6 and 7). Grain size distributions in this site are typically unimodal, except occasionally bimodal where pebble sized shells are observed. The core is highly bioturbated, with chaotic mottling observed throughout (Fig. 7). CT slices reveal localised areas of intact primary sedimentary structures, where parallel laminae are locally preserved. Broken, disarticulated bivalve shells are observed within the lower 20 cm of the core and comprise <1% volume area of the core (Fig. 7).

Although site 2 also show high content of fine fraction (avg. 70%, coarse silt with unimodal gain size distributions), it is characterised by much higher content of sand (~23–43%) than site 1 (Fig. 6). The core used for the sedimentological log was different from the one used for the grain size analyses, thus, the lengths of these are different (Figs. 6 and 7). The core showed in the sedimentological log (Fig. 7) reveals a silt dominated interval dominated of poorly-sorted, sandy silt. (Fig. 7). The core is highly bioturbated, with chaotic mottling observed throughout. Discrete macroscale ichnostructures showing sub-vertical 10 cm long burrows and horizontal wavy forms are observed at 36 cm and 44 cm depth, respectively (Fig. 7). Fragmented bivalve shells are observed throughout the core and comprise <1% volume area of the core (Fig. 7).

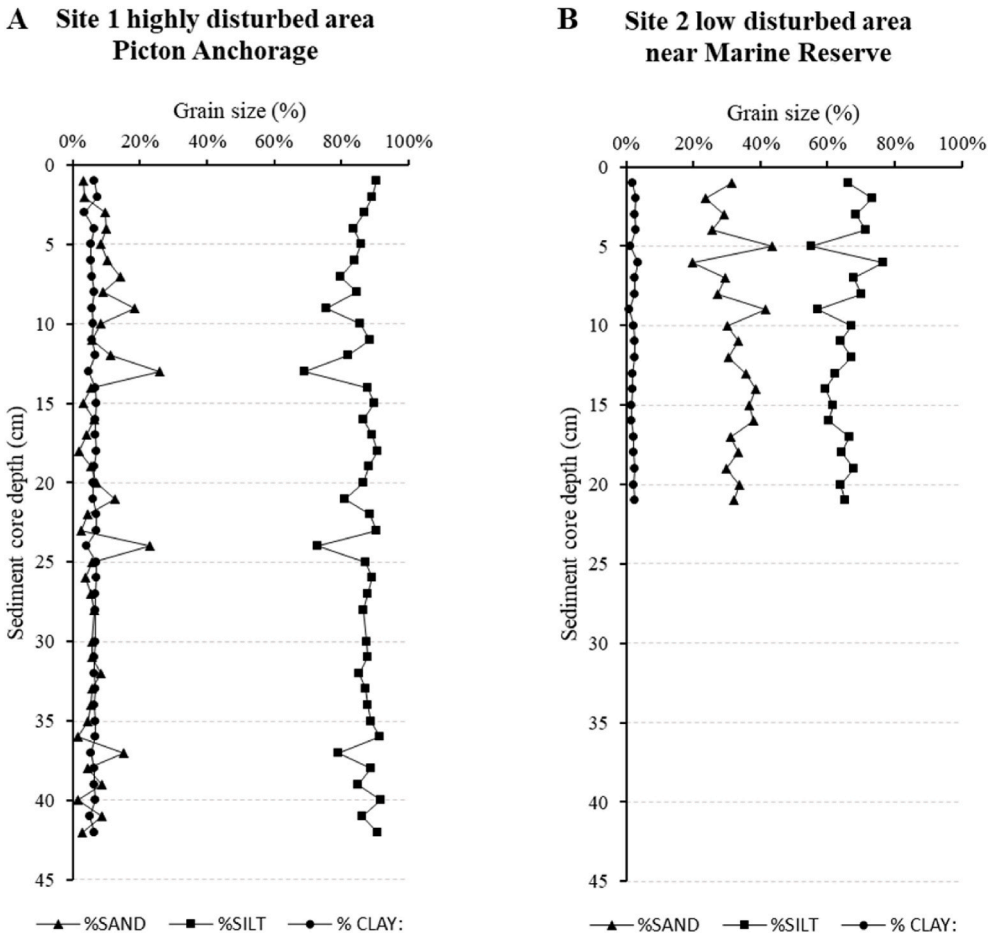

Fig. 6. Grain size distribution (i.e., each curve representing % of sand, % of silt and % of clay) through the sediment cores collected in **A)** site 1, Picton Anchorage; and **B)** site 2, adjacent to Kokomohua Marine Reserve (see location in Fig. 1; Table S2).

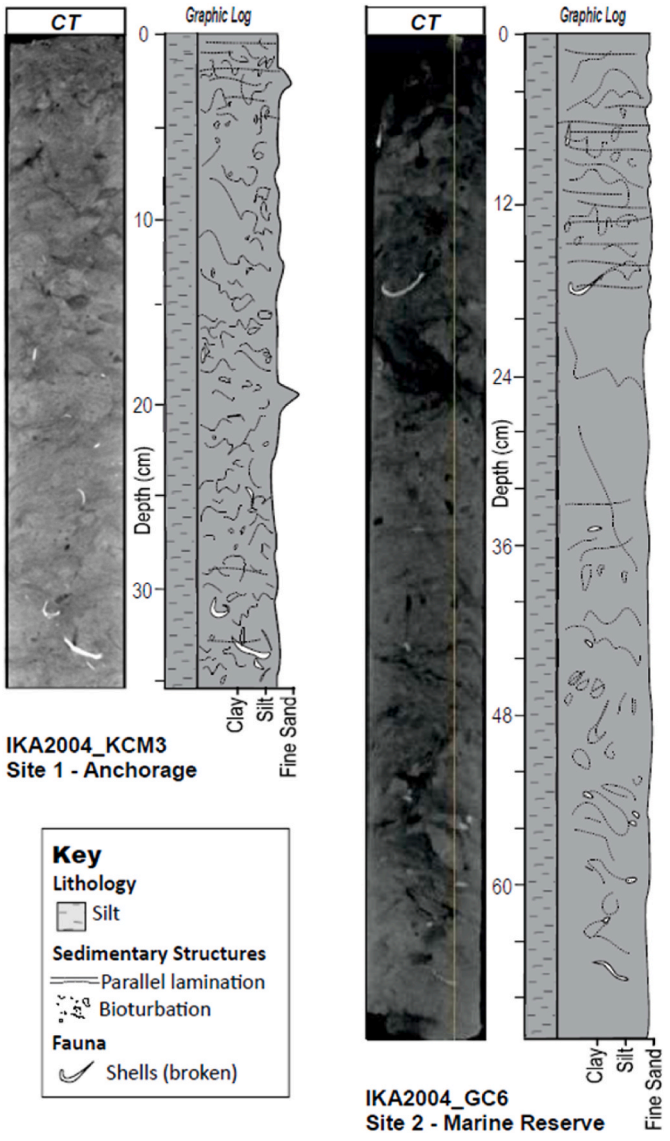

Fig. 7. Sedimentological analyses, including CT scans and core logs of the sediment cores collected in **A)** site 1, Picton Anchorage; and **B)** site 2, adjacent to Kokomohua Marine Reserve (see location in Fig. 1).

Both sampled sites had similar surface EPS concentrations within the top 2 cm (ranging from 86.78 to 100.06 μg/g) (Fig. 8). In site 1, sediment EPS content fluctuated downcore with a peak of 188.71 μg/g between 6 and 9 cm and ranging between 86.13 and 136.53 from 9 to 38 cm deep (maximum depth measured). In the site 2, sedimentary EPS content declined with depth to a minimum of 55.89 μg/g at the bottom of the retrieved core between 21 and 22 cm (Fig. 8).

4. Discussion

4.1. Distribution and concentration of microplastics in marine sediments

4.1.1. Concentrations of microplastic with distance from urbanised areas

The QCS area is characterised by low near-bottom current velocities (~0.05 m s^{-1}), which favours deposition of fine sediment fraction (Hadfield et al., 2014; Ribó et al., 2021; Watson et al., 2020), specifically in site 1 located in the inner part of QCS (Figs. 1, 6A and 7), and concurrently could enhance high accumulation of microplastic particles at the seafloor surface. site 2, located in the outer part of QCS (Fig. 1) is also characterised by low near-bottom current velocities (Hadfield et al., 2014; Ribó et al., 2021). However, being located near the mouth of the Sound, adjacent to the Cook Strait, site 2 is likely to be influenced by the wave climate and storms inducing some resuspension and mixing of the bottom sediments, similar to other regions in the Cook Strait (Carter and Heath, 2010; Lewis, 1979). The large amount of microplastic particles found in the surface sediments at both sampling sites (i.e., top 5 cm; Fig. 3) indicates widespread plastic pollution in the area, showing effective microplastic transport in the QCS region from input locations (e.g., particles being easily transported with currents (Baudena et al., 2023)).

Our results revealed four times more microplastic particles accumulated in the top 5 cm within the marine sediments near the Kokomahua Marine Reserve (site 2) than in Picton Anchorage (site 1). Concentrations of microplastics found near the Marine Reserve (site 2), 30 km from the Picton township, peaked in the surface layers (n = 22) and at 40 cm below the seabed (n = 17). The relatively low concentrations at site 1 (n = 59), near the Picton township compared to the distal site 2 (n = 85) either demonstrates microplastic transport away from populated areas, or may suggest the Kokomahua has a more proximal aquatic source of plastic pollution.

Sediment mixing implied by the EPS profile supports our hypothesis that significant disturbance at site 1 is mixing plastic particles down the profile of the sediment core. EPS concentrations are commonly considered to be a proxy for vertical displacement of microphytobenthic algae (Orvain et al., 2014; Pierre et al., 2012; Underwood and Paterson, 2003). We would expect EPS, which in shallow marine environments is predominantly produced in abundance by near-surface dwelling microphytobenthos, to be greater at the sediment surface. Therefore, increased EPS concentrations at depth in the sediment cores would suggest that a significant proportion of microphytobenthic biomass (and associated EPS) was transported to depth through sediment reworking (Richard et al., 2023). In the case of the anchoring site, where sediment EPS concentrations are larger at depth (>35 cm deep) than at the surface, and EPS concentrations are similarly distributed throughout the sediment core, we propose to be due to high levels of sediment disturbance at both the surface (top 10 cm) and at depth (>35 cm) consistent with anchoring (Watson et al., 2022). The EPS mixing profile at site 2 also corroborates our hypothesis that surface deposited plastics are less mixed into the subsurface sediment, especially at the top 5 cm layers, with any human-made disturbance occurring at this site, but with (supposed) average bioturbation rates consistent with a typical shallow marine environment.

These outcomes suggest that while in areas where human activities are strictly regulated, such as site 2 and MPAs in general, there are potentially higher accumulation of plastic (and other contaminants, such as heavy metals), especially at the surface seafloor layers (top 5 cm).

4.1.2. Microplastic concentrations downcore

We observed high abundance of particles in the top 5 cm at both sites, at 35 m (site 1) and 24 m (site 2) water depth (Fig. 1). This is consistent with findings of other studies conducted worldwide (e.g., (Courtene--Jones et al., 2020; Zheng et al., 2020); among others). However, the concentrations of microplastic particles downcore in Picton Anchorage (site 1) remain moderately constant throughout the entire sediment core

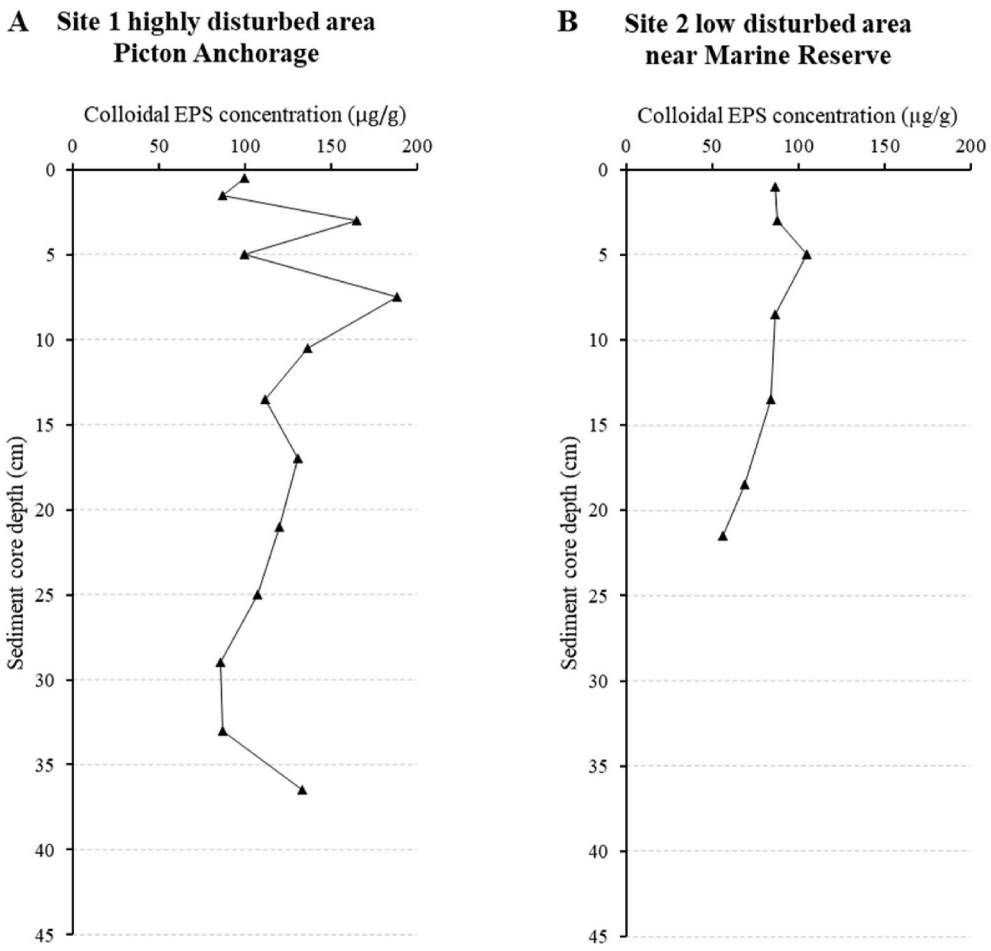

Fig. 8. Colloidal EPS concentration through the sediment cores collected in **A)** site 1, Picton Anchorage; and **B)** site 2, near Kokomohua Marine Reserve (see location in Fig. 1; Table S3).

(Fig. 3). This near-homogenous vertical distribution of microplastic particles in the Picton Anchorage site suggests that other physical seabed disturbances (e.g., including ship anchoring and deep mixing) are reworking microplastic particles accumulation, resulting in higher concentrations at depth, rather than particle distribution decreasing with depth, as we initially hypothesised. Previous research shows that the seabed at the Picton Anchorage site is scoured by anchoring practices, excavating up to 80 cm of sediment (Watson et al., 2020). We suggest that overturning of sediment by anchors enhances the vertical mixing of plastic particles below surface sediment, resulting in relatively high concentrations of microplastic downcore (Fig. 3A). Additionally, this disturbance is potentially altering the texture of the sediments (e.g., resulting in the high percentage of silt fraction throughout the entire sediment core, Figs. 6A and 7), similar to the effects of bottom trawling in other areas worldwide (Oberle et al., 2016).

At site 2, near the Kokomohua Marine Reserve, the concentration of microplastic particles is much higher in the surface sediments, decreasing with depth until ~40 cm, where concentrations are elevated to near-surface levels (Fig. 3B). Here, we presume a lower human footprint, with microplastic particles sinking and accumulating into the seabed. In this scenario, where we expect the sediments to be less disturbed by human activities, microplastic particles tend to accumulate in the surface layers (top 5 cm) with abundance decreasing downcore. The elevated microplastic concentration at ~40 cm could be caused by various reasons including: i) enhanced bioturbation, ii) legacy plastic accumulation, iii) storm induced plastic accumulation. The presence of larger and longer-lived bioturbating species and functional groups, e.g., downward conveyor species, in the less disturbed environment (Hale et al., 2017), may favour the transport of microplastic particles deeper down into the seabed. Alternatively, the peak in microplastics at ~40 cm could be related to legacy plastic accumulation that occurred prior to when this area was declared Marine Reserve in April 1993. The high concentration of microplastic particles at depths of ~40 cm below the seafloor may represent a high energy storm event, where plastics were transported and deposited due to enhanced current conditions (Baudena et al., 2023; Nakajima et al., 2022). Additional analyses to determine the sediment age and the sedimentation rates in this region would be needed to verify the microplastic accumulation rates and discriminate the reason of the elevated concentration of microplastic downcore.

4.2. *Types of microplastic particles found in the marine environment*

Seven main different polymer types (PTFE, PET, PVB, PP, n-BMA, PVA and acrylic acid) were identified (Fig. 4) in the sediment samples collected, indicating multiple sources of plastics entering the region of QCS (Fig. 1). The three major types of polymers distinguished are all used in *i)* the maritime industry, including substances for corrosion protection of engineered components in the marine environment (PTFE or Teflon used substitute of past choices, such as galvanising, zinc and cadmium painting), fishing lines (and PP) and aquaculture materials

(PP); and *ii)* in common food packaging (PET). These materials could easily be released in the marine environment from land and/or maritime and leisure activities (e.g., fishing, commercial and recreational boats, aquaculture), becoming the source of plastic pollution in areas near the Picton coastal township (site 1) and subsequently transported reaching the open ocean in the Marine Reserves region (site 2).

The Picton Anchorage (site 1) had substantially fewer polymer type results compared to the Kokomohua Marine Reserve (site 2), and our preliminary findings suggest the profile of polymer types between the two sites is distinct. This may reflect differences and different combinations of sources of microplastics to these sites, e.g., the Kokomohua Marine Reserve (site 2) may include aquatic sources that are not present in the Picton Anchorage site (site 1).

5. Conclusions and implications of this research

It is globally recognised that protected areas are needed to battle degradation of ecosystems and biodiversity loss (IUCN, 1980). Currently ~8% of the global ocean is covered by protected areas (UNEP-WCMC, 2022), and UN member countries have pledged to protect 30% of the global ocean by 2030. Within these MPAs, Marine Reserves provide the highest level of protection, from the sea surface to the seafloor; however, protected areas are still vulnerable to external influences, specifically stressors such as plastic pollution (Barnes et al., 2018; Hatzonikolakis et al., 2022; Kelleher, 1998; 1999; Luna-Jorquera et al., 2019).

This study is the first to isolate, quantify and determine the composition of microplastics within New Zealand's marine sediments (i.e., water depths below the subtidal zone). The obtained results reveal that microplastic are spatially extensive across the QCS, with plastics contamination reaching at least 40 cm below the seabed. Downcore trends in microplastic show four times more microplastics accumulated in the seafloor surface (top 5 cm) within the Kokomohua Marine Reserve area than near the coastal township of Picton. Near-homogeneous vertical distribution was observed at the Picton Anchorage, suggesting enhanced mixing of plastic particles below the seafloor surface that we attribute to the physical disturbance, which could be caused by natural processes (e.g., bioturbation or storm events) and/or human activities (e.g., ship anchoring). Conversely, in the presumably less disturbed area near the Marine Reserve (i.e., disturbance to be less frequent and less extensive as per area affected and in depth below the seafloor), the concentration of microplastic particles decreased with depth. However, a peak of microplastic concentration was found downcore, at ~40 cm, potentially due to bioturbation favouring particles transport down into the seabed, storm beds, or legacy plastic accumulation. Seven main different polymer types were identified within the marine sediments, all used in the maritime industry and in common food packaging, indicating they could be released in the QCS region from land and/or maritime and leisure activities. Distinct polymer types identified between the two sampled sites suggest different source of microplastic for both sites. However, the main potential source of plastic pollution would be the areas near the Picton coastal township, and microplastic particles would be transported by currents reaching the distal areas near the Marine Reserve, and ultimately the open ocean out Cook Strait.

Over the past decade the number and size of MPAs has grown around the world, however these areas are often located close to the accumulation zones of anthropogenic marine litter (Luna-Jorquera et al., 2019). With the growing threat of plastic pollution in the marine environment, affecting biodiversity, ecosystem functioning and ultimately human well-being it is crucial to assess the accumulation of microplastic particles in the seafloor.

When monitoring the effectiveness of MPAs, the impacts of stressors such as microplastic accumulation should be considered – particularly in regard to impacts on carbon sequestration (e.g., degradation of plastic particles can shift biogeochemical processes within marine sediments, impacting carbon and nutrient cycling and even leading to genetic shifts in microbial communities).

Microplastic particles present a unique environmental problem. As plastic particles become embedded within seafloor sediments, they have detrimental impacts to marine ecosystems and upstream consequences for the people, industries and cultures that rely on them. Although the presence of microplastics in the marine realm is becoming more widely established, there is still limited knowledge about how microplastic accumulates and disperses in marine sediments, or what implications this has for ecosystem function. In order to better predict the distribution and the final sink of microplastic particles in marine environments in New Zealand and worldwide, we recommend that future research considers *i)* the drivers of spatial and temporal distribution and accumulation of microplastic particles in the seabed; and *ii)* the severity and impact of microplastic pollution in benthic ecosystems.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.csr.2023.105115.

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