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Review

The fate of microplastic in marine sedimentary environments: A review and synthesis

Peter T. Harris

GRID-Arendal, P.O. Box 183, N-4802 Arendal, Norway

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ABSTRACT

A review of 80 papers on microplastic (MP) particles in marine sediments was conducted for different sedimentary environments. The papers were assessed for data on average MP concentration, MP morphotype (fibres, fragments, films, etc.), MP particle size distribution, sediment accumulation rates and correlations with total organic carbon (TOC) and sediment grain size. The median concentration of MP particles is highest in fjords at 7000 particles kg^{-1} dry sediment (DS) followed by 300 in estuarine environments, 200 in beaches, 200 in shallow coastal environments, 50 on continental shelves and 80 particles kg^{-1} DS for deep sea environments. Fibres are the dominant MP type and account for 90% of MP on beaches (median value) and 49% of particles in tide-dominated estuaries. In order to advance our understanding of the fate of MP in the ocean, quantitative assessments are needed of MP flux rates (g m^{-2} $year^{-1}$) in a range of sedimentary environments.

1. Introduction

1.1. Plastics as sediment particles

Plastic pollution in the oceans has attained levels that have captured the attention of the global community (UNEP and GRID-Arendal, 2016; Borrelle et al., 2017). Plastic has been found in all parts of the marine ecosystem (Geyer et al., 2017) from seafood to the most remote environments on Earth including the bottom of the deepest ocean trenches (Fischer et al., 2015; Peng et al., 2018). The ocean receives plastic waste, 80% of which enters from the land mainly via rivers and 20% from the sea (mainly lost fishing gear; Ritchie and Roser, 2020). All of it is eventually deposited in marine sediments, the ultimate sink for many pollutants (Woodall et al., 2014).

Plastic particles are solid, transportable forms of matter and are thus included in the discipline of "physical sedimentololgy" according to the definition provided by Allen (1985). It is therefore reasonable to ask what can be learned from the field of sedimentology to guide our understanding of the fate of plastic in the marine environment and thus inform management decisions. The fate of solid plastic particles in the environment might be expected to mirror the fate of sediment particles that have hydraulically equivalent physical properties (Kane and Clare, 2019). Furthermore, since plastic has been dispersed into the marine environment in significant quantities over only the last ~70 years, this represents an instantaneous event (in geologic time) and hence provides an opportunity to test concepts in sedimentology whereby plastic waste can be used as a passive tracer for the transport of sediment into marine depositional environments.

The concept of hydraulic equivalence is of critical importance to employing the "plastic as sediment" analogy (Enders et al., 2019; Kane and Clare, 2019). Where hydraulic equivalence can be determined to exist between specific plastic and sediment types, the standard, conceptual facies models for commonly found depositional environments can be used to predict the likely fate of plastic in the marine environment. This concept underpins the present study as well as numerical (hydrodynamic) modelling of the fate of plastic in the marine environment (e.g. Hardesty et al., 2017; Koelmans et al., 2017; Atwood et al., 2019; van Wijnen et al., 2019).

Hydraulic equivalence means that a plastic particle having a particular size, shape and density, will behave in the environment in a way that is comparable to a naturally occurring sediment particle of known size, shape and density. The standard used in sedimentology for density and shape is a quartz sphere (e.g. Leeder, 1982), and quartz has a density of 2.65 g/cm^3. In contrast, the density of plastic particles ranges from around 0.9 to 1.4 g/cm^3 (Table 1). In fact, the density of most naturally occurring minerals is greater than plastic, ranging between around 1.7 and 3.0 g/cm^3. It is also true that most natural grains are not perfect spheres but instead have a broad range of shapes, the same as for plastic particles as seen in images from published field studies (e.g. Fischer et al., 2015; Ling et al., 2017). Differences in density and grain

E-mail address: Peter.Harris@grida.no.

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Table 1
Density of different types of plastic particles compared with the density of naturally occurring sediment particles.

Density g/cm^3	Chemical name	Common example
Anthropogenic plastic particles		
0.92	Polypropylene (PP)	Bottle caps, rope
0.95	Polyethylene (PE)	Plastic bags
1.01–1.09	Polystyrene (FPS)	Floats, containers
1.15	Polyamide (Nylon)	Fishing nets, clothing
1.24	Cellulose acetate	Cigarette filters
1.3	Polyvinyl chloride (PVC)	Plastic film
1.35	Polyesther	Clothing
1.39	Polyethylene terephthalate (PET)	Plastic bottles, carpet, clothing
1.5	Rayon	Clothing
Natural particles		
0.9–1.3	Organic matter	Wood, leaves, algal debris
1.7–2.0	Montmorillonite	Clay
2.16–2.68	Kaolinite	Clay
2.65	Quartz	Beach sand
2.71	Calcite	Coccoliths, bivalves, gastropods
2.95	Aragonite	Corals, pteropods, bivalves, gastropods

shape go some way towards explaining the poor correlation often found between the sizes of plastic and natural sediment particles deposited at the same location (e.g. Browne et al., 2011).

However, naturally occurring organic matter, such as wood, leaves and marine algal debris, have typical densities ranging between 0.9 and 1.3 g/cm^3 (Table 1) which are comparable to plastic. Also, sand, silt and clay-sized particles can theoretically have hydraulic equivalence with larger-sized plastic particles in spite of differences in density (Enders et al., 2019; Fig. 1A) and some studies have reported correlations between plastic particle size and wave/current energy (Ling et al., 2017; Enders et al., 2019). Thus, to a first approximation, it might be expected that the fate of plastic in the marine environment is similar to the fate of naturally occurring organic matter together with silt- and clay-sized mineral grains since they are principally governed by the same physical laws (Enders et al., 2019).

Due to their low densities, most plastic particles < 2 mm in size are expected to be transported as suspended-load rather than bedload (Fig. 1B). This has significant implications for the fate of larger (> 2–4 mm) plastic particles. Large particles transported as bedload (rolling and bouncing along the seabed) become fractured and reduced in size. This process will continue until plastic particles are reduced to a size (i.e. around 1–4 mm depending on density) where they are no longer transported as bedload, but only in suspended load (Fig. 1B). Particles transported in suspension are not subject to the mechanical fracturing that occurs during bedload transport. Thus, there is a theoretical minimum size that every plastic particle should attain as a consequence of mechanical fracturing during bedload transport. This is identical to the creation of detrital calcareous silt from natural carbonate particles (shells) that are broken down by physical (and biological) erosion processes (Harris, 1994; Smith and Nelson, 2003; Trower et al., 2019).

Plastic particles may enter the marine environment in many forms having different densities (Table 1). Around 10% of plastics remain floating on the surface. This is the material that becomes stranded on beaches, 80% of which is cigarette butts, plastic bags, lost fishing gear and food and beverage containers (Andrady, 2015). However, around 95% of plastic particles collected in surface trawls are so-called "microplastics" (Law, 2017), which are particles > 1 μm and < 5 mm in size (particles < 1 μm are "nanoplastics" and particles > 5 mm are "macroplastics"). Microplastics (MP) most commonly occur as: a) *fragments*, created by mechanical and biological fragmentation of larger plastic items (also termed "secondary" plastics); b) *microfibres* derived from the fragmentation of synthetic fabrics and ropes (Browne et al., 2011); and c) *microbeads* manufactured as abrasives used in cosmetics (Fendall and Sewell, 2009; Mason et al., 2016). Though not as visible to the human eye as larger macroplastic plastic debris, MP are perhaps a greater risk to the environment than macroplastics due to their ingestion and uptake into the food web (Cole et al., 2011). In their study of the Belgian continental shelf, Van Cauwenberghe et al. (2013a) estimated that the mass of MP in the environment to be 400 times greater than the mass of macroplastics.

MP particles suspended in seawater in the global ocean are estimated at 93,000 to 236,000 metric tonnes, with large errors of estimation outside the North Atlantic and North Pacific gyres where the best data exist (Law, 2017). These figure account for only ~1 to 3% of the plastic waste estimated to enter the ocean from land in a single year (Jambeck et al., 2015). Thus it appears that most MP particles are either not reaching offshore to the deep sea environment, or (if they are) they are not remaining in suspension for any length of time, but rather they are exported to the ocean floor; plastic particles that are less dense than seawater eventually sink as a result of biofilm formation (Lobelle and Cunliffe, 2011), expelled as faecal pellets (Cole et al., 2013), or through flocculation and sinking as aggregates (Long et al., 2015; Bergmann et al., 2017; Michels et al., 2018).

1.2. Microplastics in the context of natural sediment transport systems

From the outset it is important to place plastic pollution within the context of natural sediment transport systems. Humans currently produce approximately 360 million tonnes/year of plastics (PlasticsEurope, 2019) and it is estimated that ~8–14 million tonnes/year enters the ocean (about 3% of all production); some is lost or deliberately thrown overboard from ships, but most enters the marine environment from the land via rivers (Jambeck et al., 2015). This figure (8 million tonnes/year) can be compared with about 12.5 billion tonnes/year of sediment delivered by rivers to the coastal marine environment (Syvitski et al., 2005). The mass of sediments entering the oceans per year is therefore ~1500 times greater than the mass of MP particles. Furthermore, the total load of particulate organic matter (POM) reaching the oceans from all rivers is estimated to be around 200 million tonnes/year (Hedges et al., 1997), which is ~25 times greater than the mass of plastic (i.e. plastic currently equals approximately 4% of POM entering the oceans).

Given their comparable densities, the comparison of MP with organic matter in terms of their behaviour as sediment particles is particularly compelling. Organic matter enters the marine environment from rivers in two forms: dissolved organic matter (DOM; particles < 0.05 μm) and particulate organic matter (POM; particles > 0.05 μm). The total load of organic matter reaching the ocean is about 400 million tonnes/year which is equal to approximately 1% of total carbon sequestered through terrestrial primary production. The fates in the marine environment of organic matter in its different forms, dissolved and particulate, are very different and play different roles in the Earth's carbon cycle (Hedges et al., 1997; Blair and Aller, 2011; Kandasamy and Nath, 2016).

Studies of organic carbon stored in coastal sediments shows clearly that DOM is rapidly remineralised and incorporated into the biosphere. On the other hand, POM is mostly trapped in estuarine and deltaic sediments within the silt-clay size fraction. According to Hedges et al. (1997, p. 205) POM "settles rapidly through the marine water column and typically accumulates to suboxic depths of coastal and marine sediments within periods of decades to centuries". A general pattern is that the highest concentrations of POM are found in rapidly accumulating sediment deposits and/or in depositional environments where the overlying water is oxygen depleted (Blair and Aller, 2011). For comparison, Seiter et al. (2005) estimate that only around 0.5 million tonnes/year of POM reaches the deep ocean floor, and only a small portion of this is terrigenous POM (the bulk is mainly from ocean

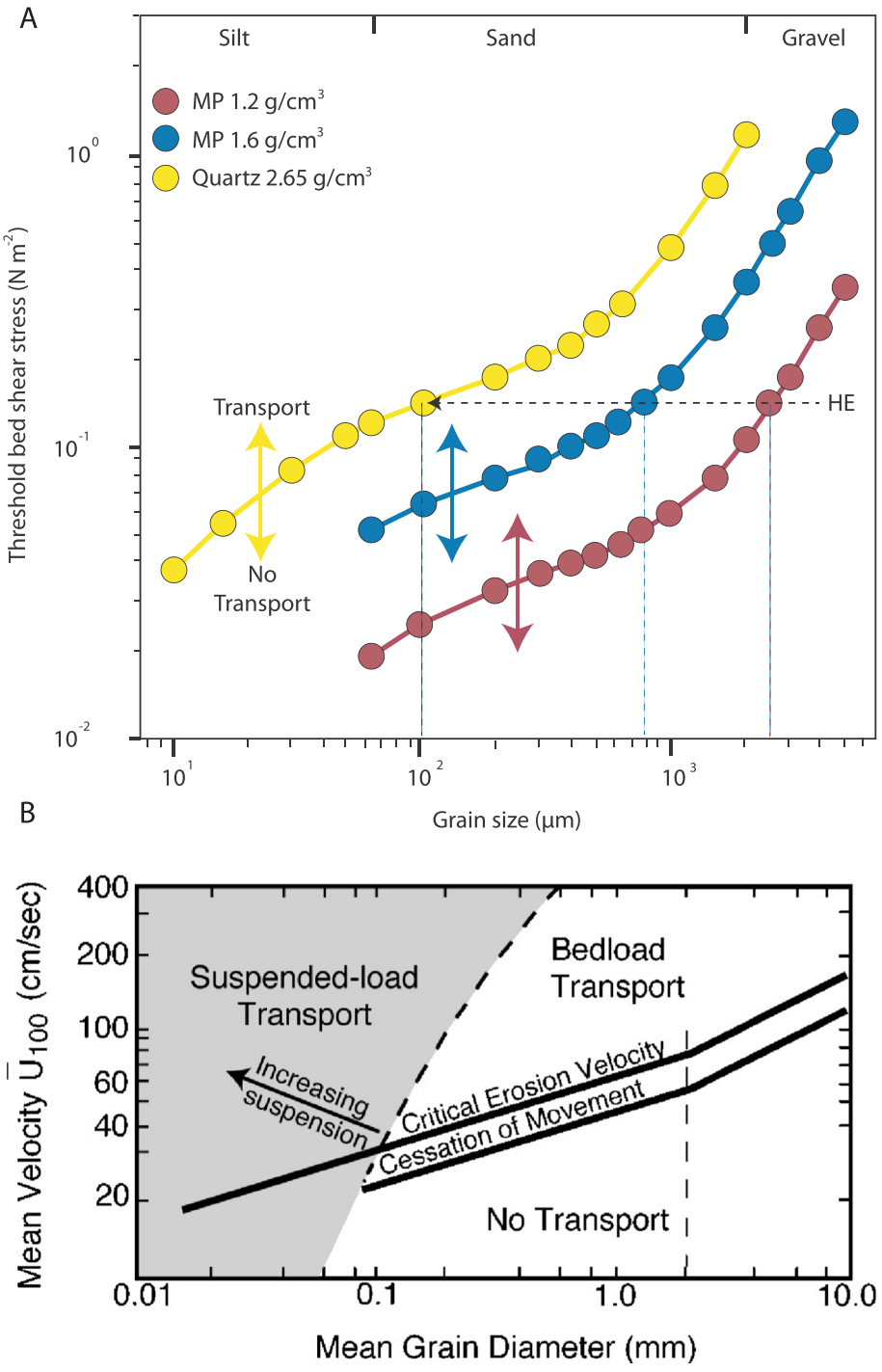

Fig. 1. (A) Plot of shear stress imparted on the seabed by a current required to mobilise sediment (and plastic) particles of varying densities and grain sizes (from Enders et al., 2019). The arrows illustrate how plastic particles with different densities are mobilised at the same level of bed shear stress (HE = hydraulic equivalence) needed to mobilise smaller sized quartz grains. For example a plastic particle having a density of 1.6 g/cm^3 and 700 µm in diameter is mobilised at the same bed shear stress as a quartz sphere of density 2.65 g/cm^3 but only 100 µm in diameter. (B) Hjulstrom diagram showing the relationship between flow speed referenced to 100 cm above the bed (U_{100}), grain size, erosion and transport of quartz density spheres in two fundamental modes of sediment transport, suspended-load and bedload. The diagram shows how a 0.1 mm diameter quartz sphere is transported as suspended load immediately the threshold speed is reached (equal to plastic particles having a density of 1.6 g/cm^3 and 700 µm in diameter or a density of 1.2 g/cm^3 and 2000 µm in diameter).

primary production). The fate of POM in the marine environment will thus vary between coastal, estuarine, deltaic, continental shelf and deep ocean sedimentary environments to the extent that rates of deposition of silt and clay sized sediment fractions and bottom water oxygenation processes vary among these different depositional environments. The fate of POM can thus be contrasted with that of plastic in as much as plastic is not transformed to a different state by oxidation or consumption by bacteria or other marine life; plastic particles persist in places where POM does not survive.

There are many textbooks available that explain the common pathways for sediment transported by rivers, glaciers and wind to the coast and its dispersal into the marine environment. As a general rule, sediments transported by rivers to the coast are effectively trapped in estuarine and deltaic sedimentary environments (e.g. Coleman and Wright, 1975; Allen et al., 1980; Walsh and Nittrouer, 2009). Sediment trapping is enhanced in estuaries by the transition from freshwater to saltwater, where sediments suspended in the fresh river water, mix with salt water giving rise to the so-called estuarine turbidity maximum (Burchard et al., 2018). Here, fine sediment particles are combined into "flocs" that rapidly settle to the seabed. Fjords have the greatest sediment trapping efficiency of all coastal sedimentary environments and are important globally as net sinks for organic carbon (Smith et al., 2015).

Due to tidal wave deformation (enhanced asymmetry in ebb and flood tidal currents), sediment is transported landward from the ocean into estuaries (Meade, 1969). This process is most pronounced in

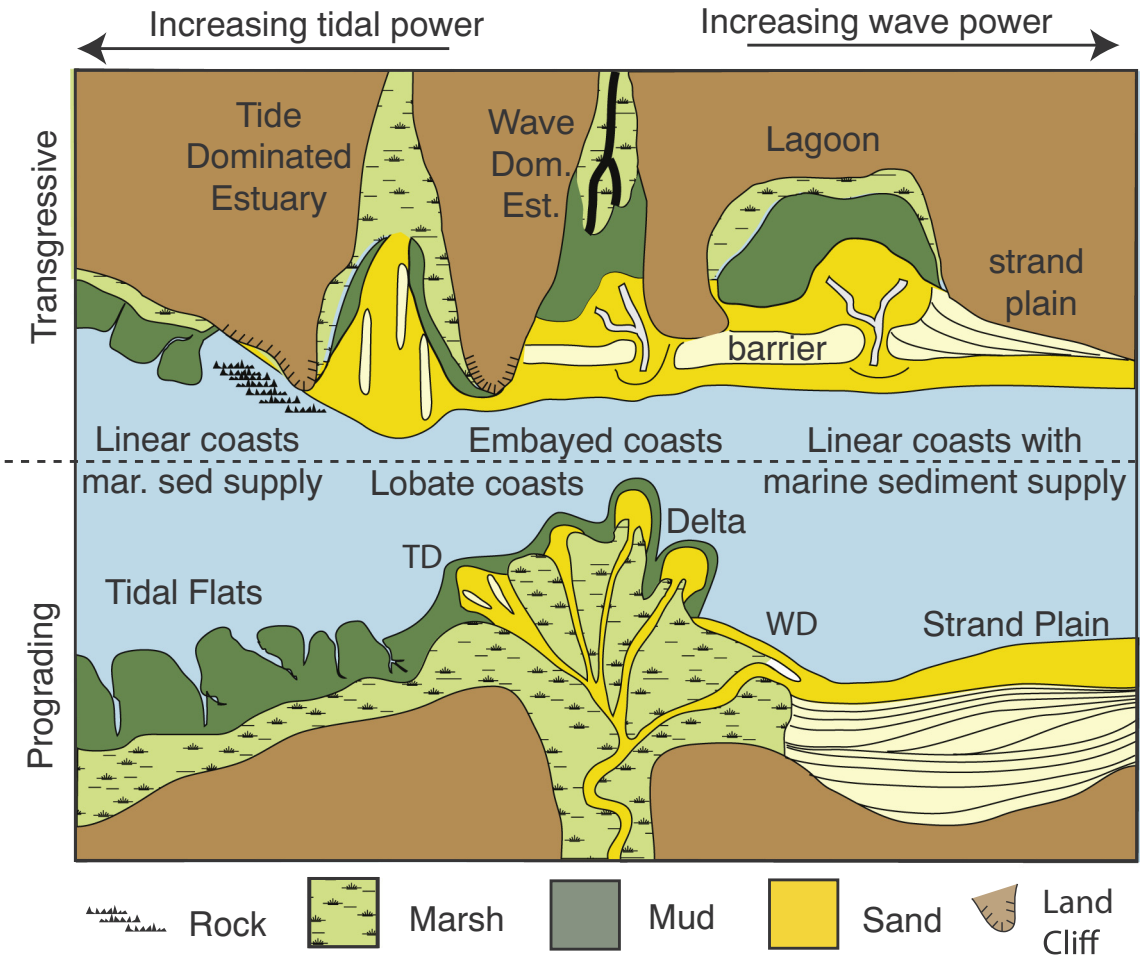

Fig. 2. Conceptual model of coastal depositional environments (after Boyd et al., 1992) illustrating differences between prograding versus transgressive environments along coasts of varying degrees of relative tide and wave power. Prograding systems include tidal flats, tide-dominated deltas (TD), bird's foot deltas, wave-dominated deltas (WD) and broad strand plains. Transgressive systems include tide-dominated estuaries, wave-dominated estuaries, lagoons and narrow strand plains.

macrotidal estuaries and deltas having mutually-evasive ebb and flood dominated channel systems (Harris, 1988; Harris et al., 2004). Geologists therefore define an "estuary" as "the seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial processes" (Dalrymple et al., 1992).

Estuarine and deltaic facies models have end-members associated with wave-dominated and tide-dominated processes operating on transgressive versus prograding continental margins (Boyd et al., 1992). Estuaries occur on transgressive margins (embayed coast; Fig. 2), where sediment supply has been insufficient during the Holocene to infill the fluvial valley which the river had incised during Pleistocene (glacial) lower sea level episodes. Wave-dominated estuaries contain a central muddy basin which is a sediment trap for fine-grained sediments (Roy, 1984). Tide-dominated estuaries are funnel-shaped in plan view and contain broad intertidal mud flats along their margins that are similarly a trap for fine-grained sediments, albeit less efficient at trapping sediment than wave-dominated systems (Harris, 1988; Wolanski et al., 2006) along with any associated MP.

Deltas are deposited along prograding coastlines where sediment supply during the Holocene has completely infilled the fluvial valley that the river had incised during periods of lower sea level such that the coastline is advancing seawards (lobate coast; Fig. 2). Tide-dominated river deltas are funnel-shaped in plan view with a seaward-prograding, delta-front clinoform, which is a trap for fine-grained sediments and where accumulation rates are measured in centimetres per year (e.g. the Fly River delta; Harris et al., 2004; Goni et al., 2008). In cases where wave and tidal energy are low, the delta may exhibit a "bird's foot" shape in plan view with a seaward-prograding, delta-front zone of accumulating silt and clay (e.g. the Mississippi River; Coleman and Wright, 1975).

In the case of wave-dominated deltas, the fine sediment fraction ("mud" which is the combination of "silt" and "clay" size fractions, defined as particles < 63 μm to > 4 μm and < 4 μm, respectively) is dispersed offshore from the coast while sand (particles > 63 μm) and gravel (particles > 2 mm) sediment is dispersed along the coastline by littoral drift. Most sandy beaches occur along wave-dominated coasts and exhibit a wide range of geomorphic and sedimentological properties governed by fundamental processes that include wave energy, tidal range, sediment supply and sea level change (Komar, 1976; Davis and Hayes, 1984; Masselink and Hughes, 2003). It is pertinent to the accumulation of MP on beaches to know if the beach is a net sediment sink (i.e. a depositional sedimentary environment), is net erosional (retreating coast) or is otherwise in equilibrium in terms of sea level, sediment supply and sediment removal processes.

Sandy beaches along exposed coasts are the most dynamic of all sedimentary environments, being continuously exposed to breaking waves and currents varying with tidal range. Sediment is transported along the coast via wave-induced littoral drift, and seasonally onshore/offshore sediment movement occurs due to seasonal changes in wave climate (winter storm waves versus summer waves), in which the upper 2+ m of beach sediment are overturned each year with the changing

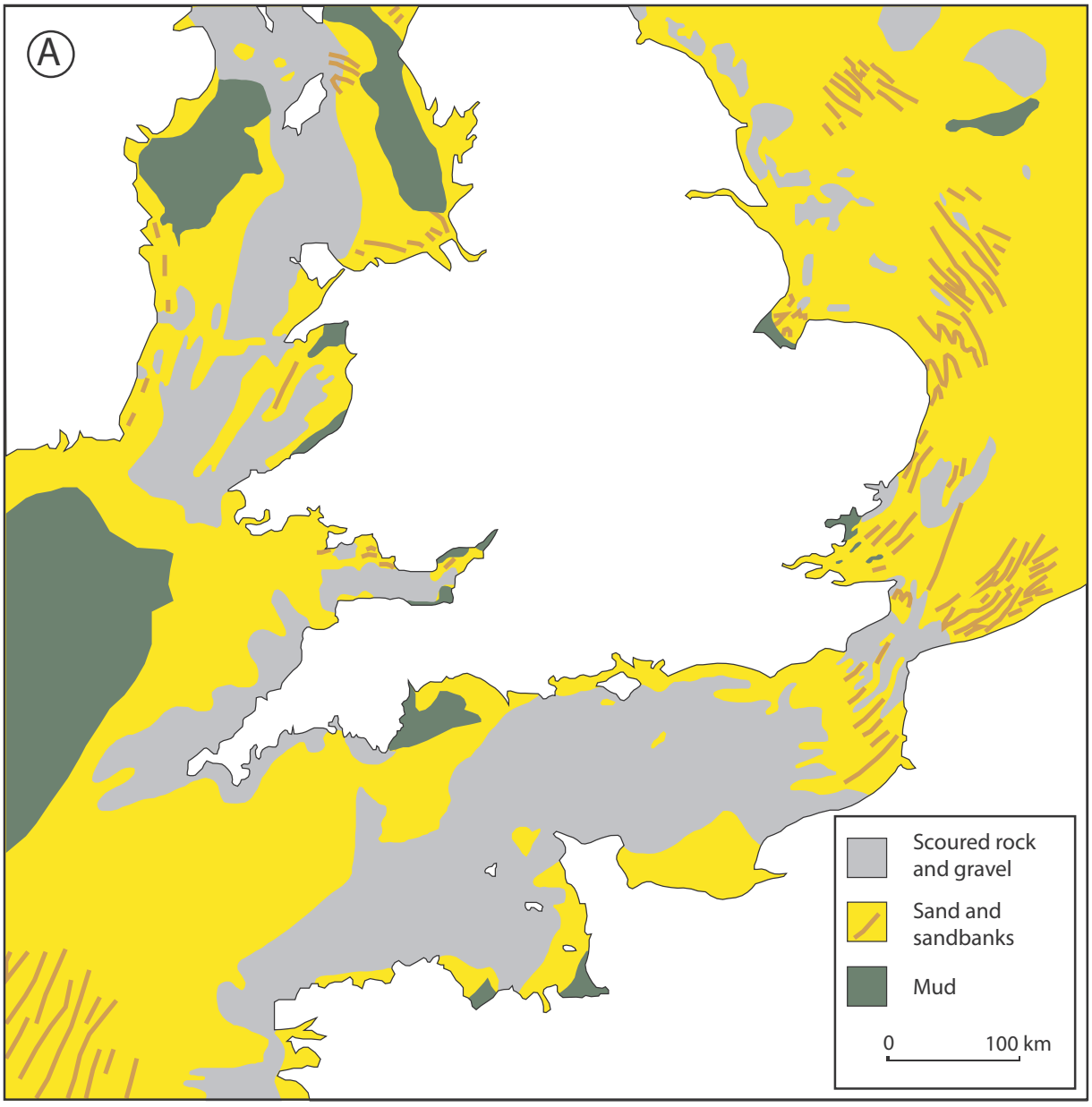

Fig. 3. (A) Example of sediment grain size distribution on the tide-dominated shelf around the southeastern United Kingdom, in which muddy sediment deposits (shown in green shading) are located towards the end of bedload transport pathways (from Harris et al., 1995); (B) example of percentage mud content on the wave-dominated shelf off Newcastle, southeastern Australia, showing the occurrence of a mid-shelf mud belt (modified from Boyd, 1980). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

seasons (Komar, 1976). Groups of large storms occurring in succession can completely re-shape a beach (Lee et al., 1998). Some factors that may influence the concentration of MP on beaches include: 1) overall tidal range and state of tides at time of sampling; 2) weather conditions such as the occurrence of storms over recent weeks immediately prior to sampling; 3) beach morphology; 4) the prevailing wave climate; and 5) sediment grain size and composition. Combinations of these factors, very few of which are accounted for in most MP studies, confound making comparisons of MP concentrations on different beaches (GESAMP, 2019).

Beach sediments found along linear, wave-dominated coasts, are commonly composed of well sorted sand and gravel from which finer silt and clay size fractions have been winnowed by waves and currents. Fine sediment that escapes from the coastal zone is deposited on the adjacent continental shelf. On tide-dominated shelves, mud is deposited towards the end of sediment transport pathways that extend from high-energy seabed scour zones and across sand-transport zones characterised by mobile sand dunes and sandbanks (Fig. 3A; Stride, 1982; Harris et al., 1995). On wave-dominated shelves, muddy sediment accumulates in shore-parallel belts located on the mid- to outer shelf, below the depth of storm wave base (Fig. 3B; Swift and Thorne, 1991; Lesueur et al., 2001; Edwards, 2002; Boyd et al., 2004).

Only a fraction of land-sourced (terrigenous) sediment escapes from present day coastal and shelf depositional environments into the deep ocean. Rare examples include shelf-sourced sand being transported down so-called “active” submarine canyons (Shepard, 1981; Puig et al., 2003, 2014; Ogston et al., 2000; Boyd et al., 2008; Walsh and Nittrouer, 2009). In their global survey of submarine canyons, Harris and Whiteway (2011) found that only about 3% of shelf-incising canyons are geomorphologically linked to a contemporary fluvial system. Instead, the export of terrigenous sediment to the slope and deep sea environments takes place mainly during ice age conditions, when

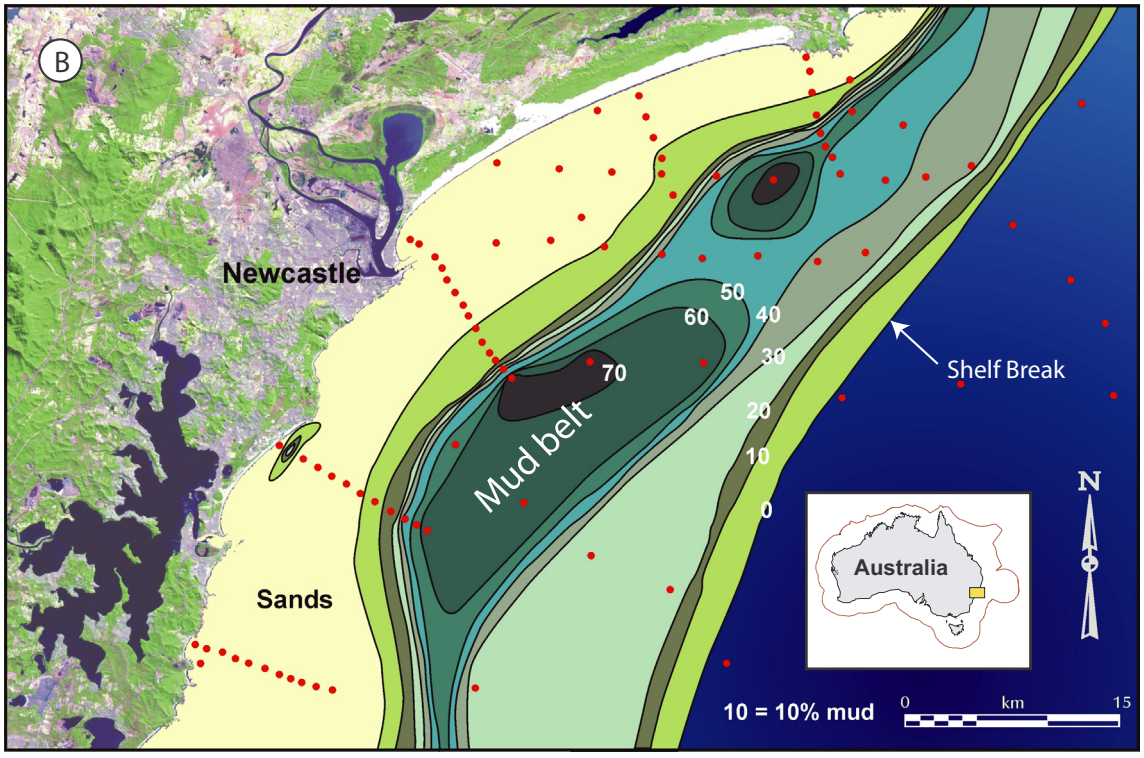

Fig. 3. (*continued*)

global sea level is lowered such that rivers cross the shelf and deliver sediment to the coast which in glacial times is located at the shelf edge; in some cases coastal sediment stored during glacial low sea level is only released to the adjacent deep sea during transgression (Dunbar et al., 2000). Thus most canyon systems are not conduits for MP from the coast to the deep ocean floor at the present time.

There is growing evidence that atmospheric transport of MP is an important mode of transport and delivery to remote environments, including the deep sea (Y. Zhang et al., 2020). Aeolian transport of "dust" (particles $<$ 20 μm in size) to the oceans amounts to about 500 million tonnes/a (Peterson and Junge, 1971). Dust is derived from desert areas where annual precipitation is $<$ 15 cm and is blown off the continents by wind and deposited in the oceans. Nickling (1994) quotes accumulation rates of aeolian dust in the Pacific Ocean of from 0.15 to 1.29 t/km^2 over the past 700,000 years. This review does not consider atmospheric transport of MP and will focus only on transport by marine processes.

1.3. Aims and objectives

Against this backdrop, what can be inferred about the fate of plastic in the marine environment based on the "plastic as sediment" analogy? As specified above, fine-grained silt and clay plus terrestrial particulate organic matter (POM) sourced from the land are generally deposited close to the coastline, mainly within estuarine and deltaic sedimentary environments. This raises the question: Are most microplastic particles also deposited in coastal, estuarine and deltaic sedimentary environments?

The aim of this paper is to assess the extent to which the observed occurrences of plastics found in marine sediments match the broad patterns of sediment deposition described above. The assessment will be based on a review of the existing literature on the occurrence of microplastics in marine sediments. A second aim is to identify gaps in knowledge of the occurrence of plastic in different sedimentary environments and to identify the key variables that need to be measured in order to quantify the fluxes of microplastic into marine sediments.

2. Methods

A literature review was carried out using Google Scholar and the ISI Web of Knowledge. The keywords "microplastic", "marine" and "sediment" in combination with "estuary", "delta", "fjord", or "deep sea" were used to generate a list of possible peer-reviewed papers. In their review paper, Hidalgo-Ruz et al. (2012) reviewed 44 papers that sampled marine sediments to measure microplastics (MP). Since then, a large number of papers have been published on the subject. Using the search terms "microplastic marine sediment" constrained to the last 10 years, 2011 to (April) 2020, yields over 8600 results in Google Scholar. Searching only within the journal Marine Pollution Bulletin with terms "microplastic" and "sediment" yielded 83 papers in 2020 and 137 papers for 2019. Further constraints included that studies that did not use standard floatation separation methods for MP were generally not included. Preference was given to case studies which provided quantitative results from a specific location. Since the aim of the present study was to compare results from coastal, shelf and deep sea settings, effort was made to find studies representing these different environments from as many different parts of the world as possible. To achieve the goal of linking MP occurrence to sedimentologic factors, studies were actively sought that included grain size, sedimentation rate data and TOC content. Relevant conference proceedings, reports and dissertations were also included in this review.

From the selected publications, information was recorded regarding: (i) the sedimentary environment where samples were collected; (ii) the methods used to measure MP including the size range assessed and resulting reported values of concentration, (iii) the methods used to measure sediment grain size and whether there was any correlation found between MP and sediment grain size; (iv) whether the total organic carbon content was measured and if it was found to correlate with MP; (v) whether the MP size distribution was measured and reported; (vi) the shape of MP particles (fibres, pellets, fragments, beads, etc.); and (vii) whether the study measured or made reference to existing information on sediment accumulation rates at the MP sample site.

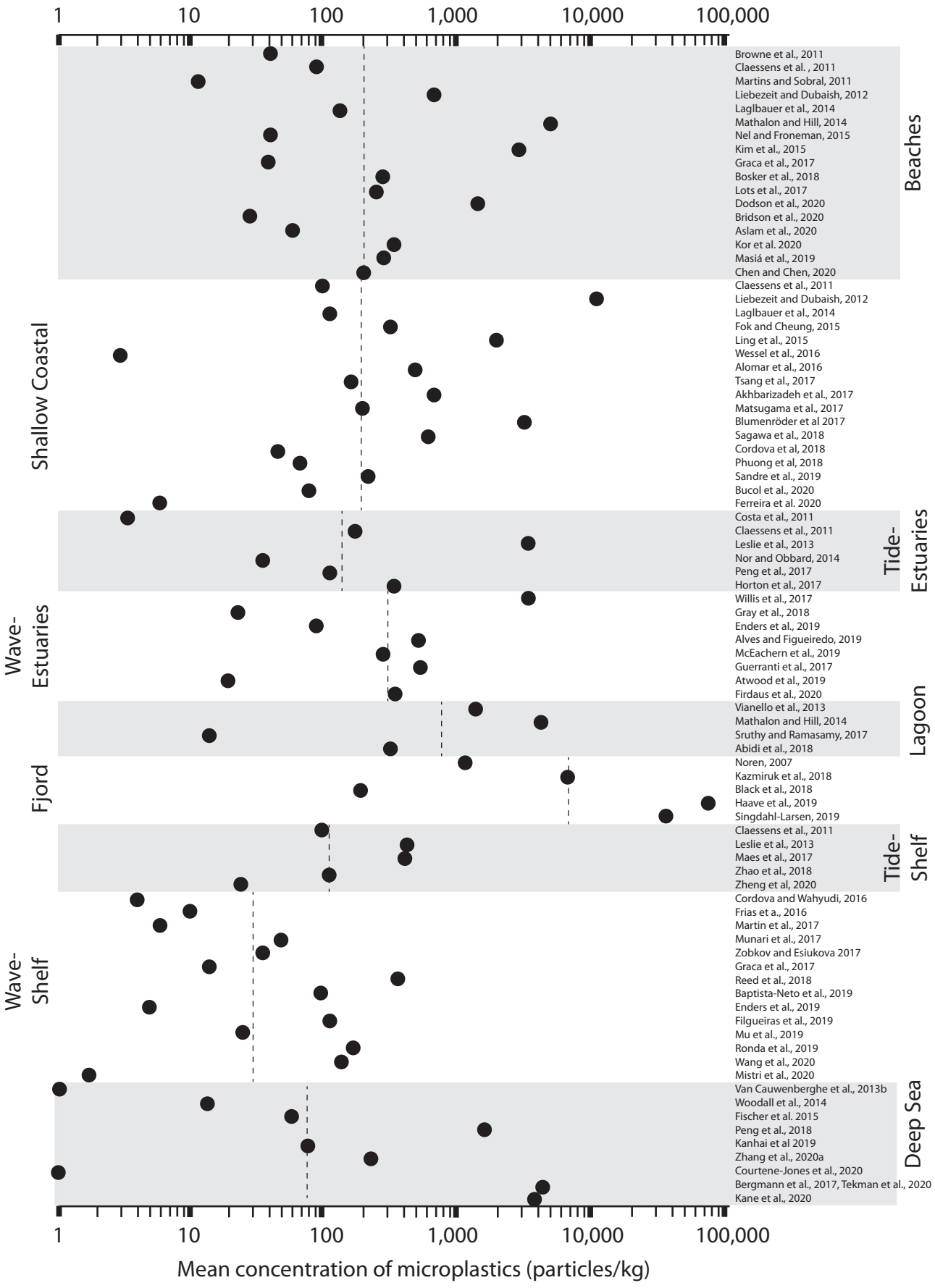

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Fig. 4. Log of mean concentration of particles kg^{-1} dry sediment reported by authors for different sedimentary environments: sandy beaches on exposed coasts; shallow water depositional environments including tidal flats and embayments; tide-dominated estuaries and deltas; wave-dominated estuaries and deltas; lagoons and coastal lakes; fjords; tide-dominated continental shelves; wave-dominated continental shelves; and deep sea environments. The vertical dashed lines are median values for each environment. Where units other than particles kg^{-1} were reported the values were converted as described in the text. Data are from: Abidli et al. (2018); Akhbarizadeh et al. (2017); Alomar et al. (2016); Alves and Figueiredo (2019); Aslam et al. (2020); Atwood et al. (2019); Baptista-Neto et al. (2019); Bergmann et al. (2017); Black et al. (2018); Blumenröder et al (2017); Bosker et al. (2018); Bridson et al. (2020); Browne et al., 2011; Bucol et al. (2020); Chen and Chen (2020); Claessens et al. (2011); Cordova and Wahyudi (2016); Cordova et al (2018); Costa et al., 2011; Courtene-Jones et al. (2020); Dodson et al. (2020); Enders et al. (2019); Ferreira et al. 2020; Filgueiras et al. (2019); Firdaus et al. (2020); Fischer et al. 2015; Fok and Cheung (2015); Frias et a. (2016); Graca et al. (2017); Gray et al. (2018); Guerranti et al. (2017); Haave et al. (2019); Horton et al. (2017); Kazmiruk et al. (2018); Kim et al. (2015); Kor et al. 2020; Laglbauer et al. (2014); Kane et al. (2020); Kanhai et al 2019; Leslie et al., 2013; Liebezeit and Dubaish, 2012; Ling et al. (2017); Lots et al. (2017); Maes et al. (2017); Martin et al. (2017); Martins and Sobral (2011); Masiá et al. (2019); Mathalon and Hill (2014); Matsugama et al. (2017); McEachern et al. (2019); Mistri et al. (2020); Mu et al. (2019); Munari et al. (2017); Nel and Froneman (2015); Nor and Obbard (2014); Noren, 2007; Peng et al. (2017); Peng et al. (2018); Phuong et al (2018); Reed et al. (2018); Ronda et al. (2019); Sagawa et al. (2018); Sandre et al. (2019); Singdahl-Larsen (2019); Sruthy and Ramasamy (2017); Tekman et al. (2020); Tsang et al. (2017); Van Cauwenberghe et al. (2013b);Vianello et al., 2013; Wang et al. (2020); Wessel et al. (2016); Willis et al. (2017); Woodall et al. (2014); Zhao et al. (2018); Zhang et al. (2020a); Zheng et al (2020); Zobkov and Esiukova (2017).

3. Results

A total of 94 studies of MP in different sedimentary environments are included in this review. These studies are reported in 80 separate publications, in which some authors reported on more than one (different) sedimentary environment in the same paper. The information gathered is presented by sedimentary environment, in order of increasing water depth from coast to deep sea.

3.1. Microplastics on beaches

The measured values of MP concentration in all environments reported in the literature range over five orders of magnitude; in beach sediments the range spans three orders of magnitude (Fig. 4). Bridson et al. (2020) reported one sample site where MP was not detected in beach sediment and the maximum value of MP concentration reported on beaches is from the high tide line on a sandy barrier island in the German Wadden Sea, where Liebezeit and Dubaish (2012) reported 496 particles in one 10 g sediment sample (i.e. 49,600 particles kg^{-1}). It is important to note that MP studies are by and large carried out in industrialised or highly populated coastal regions where high levels of pollution including MP are expected to occur. Hence the numbers reported here are biased towards polluted as opposed to more pristine sites.

Kim et al. (2015) reported a maximum of 285,673 particles m^{-2}, which cannot be directly compared with units of particles kg^{-1} without making certain assumptions. For example, assuming that the 285,673 particles m^{-2} are from the top 1 cm of sediment (285,673 particles/10,000 cm^3) and assuming a sediment dry bulk density of 1700 kg/m^3 (0.0017 kg/cm^3) then the figure is equal to approximately 16,800 particles kg^{-1}. Browne et al. (2011) reported the number of fibres (particles) in 250 ml of sediment. This unit can be converted to particles kg^{-1} by assuming the 250 ml is dry sediment with bulk density of 1.7 kg l^{-1}. Based on these assumptions, all values of MP concentration have been converted to particles kg^{-1} and average values for each study are plotted in Fig. 4. The data show that values of mean MP concentration on beaches have a median value of ~200 particles kg^{-1} (Fig. 4). Given the broad range in values the median values are given here because mean values are overly influenced by extremely large and small numbers in small sample sizes. Based on the analysis of samples from 23 European beaches, Lots et al. (2017) reported that the majority contained < 248 particles kg^{-1} which is comparable to the median value of ~200 particles kg^{-1} found here (Fig. 4).

Most of the MP reported from beaches are fibres with smaller numbers of fragments, pellets and films (Fig. 5). Five studies reported that more than ~90% of particles were fibres and all but three studies reported > 70% of particles were fibres. Lowest values were reported by Liebezeit and Dubaish (2012) who found MP was 99% "granules" (and only 1% fibres) on Wadden Sea barrier island beaches, while Kor et al. (2020) found MP was mainly fragments (33%) with a large number of films (27%) and only 30% of particles were fibres.

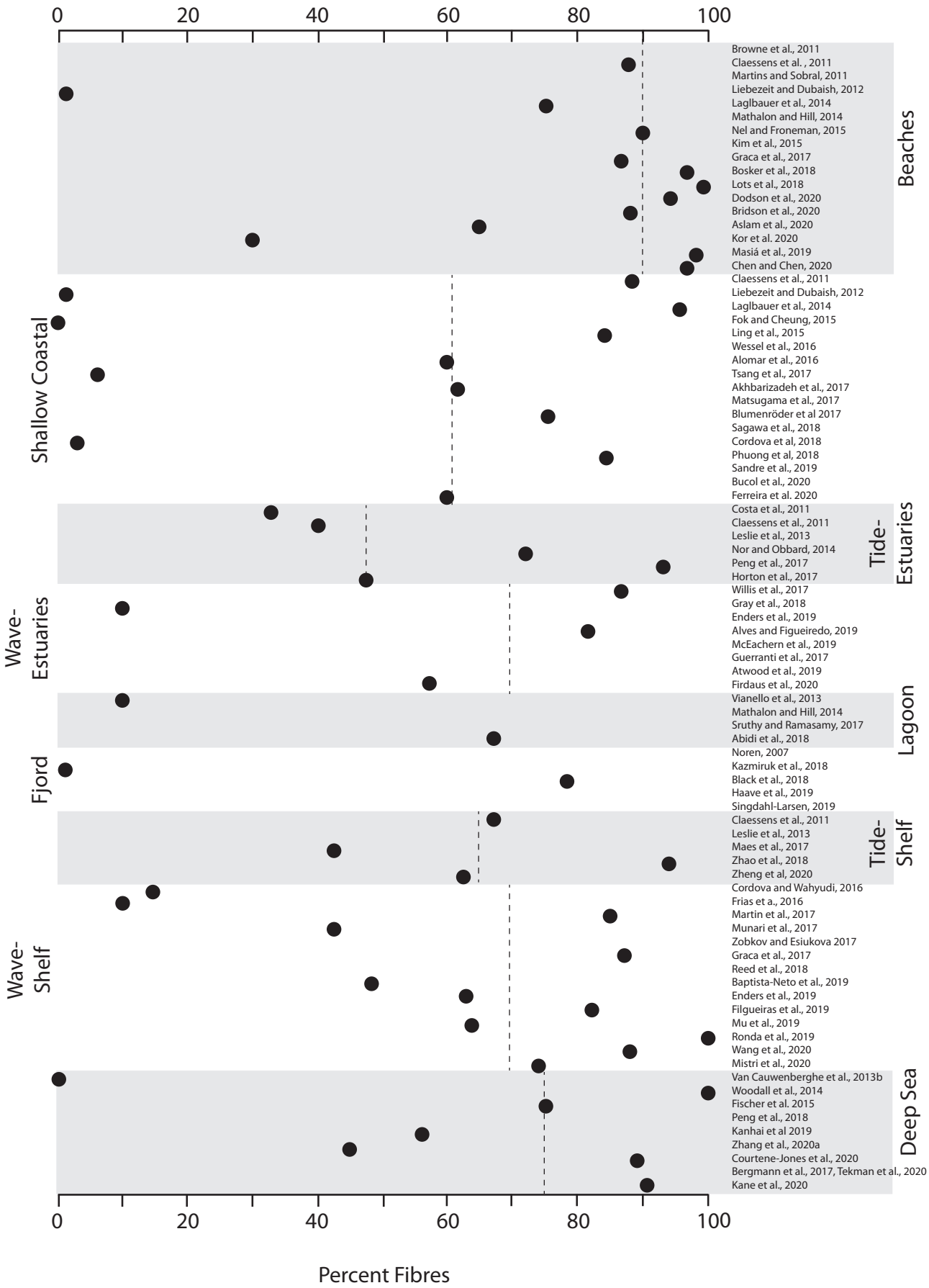
Four studies from beaches did not report on the percentage of fibres (Fig. 5). Kim et al. (2015) reported the occurrence of large numbers (87–99%) of foamed polystyrene (FPS) particles at beaches in Korea. Studies by Browne et al. (2011) and Mathalon and Hill (2014) focussed entirely on fibres and did not report on other particle types.

Apart from different reporting units, three other factors assessed in this review have an impact on the MP concentration reported: 1) sediment accumulation rate; 2) density of the liquid used in the floatation analysis; and 3) the mesh size of sieve or pore size of filter paper used in the analysis. Claessens et al. (2011) was the only study of MP on beaches reviewed here that measured or considered sedimentation rates. These authors reported sediment accumulation rates of 2–7 cm $year^{-1}$ at two core sites located on Belgium beaches and noted a 3-fold increase in plastic content between 1993 and 2008. Accumulation rate will affect the concentration of MP measured in the top 1–5 cm of beach sediment (the most common sample depth). If the rate is slow (~1 mm/year or less) the upper 5 cm will contain the full inventory of all MP deposited since the mass production of plastic began (MP is concentrated). Where sediment accumulation rates are fast (~1 cm $year^{-1}$ or more) the top 5 cm of sediment will contain only the most recent input (MP is diluted).

The density of liquid used to extract MP illustrates that overall, 71 of the 80 studies used a liquid with a density of 1.2 g/cm^3 or greater (Fig. 6). Among beach studies, 5 used a liquid density > 1.5 g/cm^3. Where the density of any MP is greater than the density of the liquid used to achieve floatation, that MP will not be included in the assessment.

Once the floatation part of each extraction is complete (in studies that use the flotation method), the supernatant containing the concentrated MP is sieved or filtered, at which stage the finest size fraction is discarded. The size of the sieve or filter used, therefore, affects the mass of MP recovered as well as the frequency size distribution of the MP. Overall, 53 out of 80 studies used a filter/mesh < 4 μm in size but 14 studies used sieves > 100 μm in size (Fig. 6). The inconsistency in methods used in separating MP from sediments is a recurring topic in MP research mentioned by many authors (see reviews by Hidalgo-Ruz et al., 2012, Hanvey et al., 2017 and Miller et al., 2017) and is discussed further below. The lack of consistency in the methods used to separate MP from sediment (Fig. 6) precludes any detailed statistical comparison of MP concentration values between different sedimentary environments, but does allow for broad indications to be inferred from the existing data in this review.

In the beach studies reviewed here the sieve mesh or filter pore size ranged from 1 mm (Kim et al., 2015, study of polystyrene on beaches of Korea) to 0.2 μm (Masiá et al., 2019, study of pocket beaches in the Bay of Biscay, Spain; and Dodson et al., 2020, study of MP on beaches in Virginia and North Carolina). Verification that all MP reported in published papers is actually plastic is beyond the scope of this review and the values reported are assumed to be correct.



(caption on next page)

Fig. 5. Percentage of MP in studies that were described as fibres (also filaments). The vertical dashed lines are median values for each environment. No value is shown for studies that did not report a percentage for the type of MP particles occurring. Fibres exceed 50% of particles in 42 of the 61 studies shown here. There is no correlation between the number of fragments and the percentage of fibres.

In order to explore for relationships between MP concentration and sediment grain size, papers were reviewed to search for any analyses of sediment size. Two of the 17 beach studies collected sediment grain size data by sieve analysis (Mathalon and Hill, 2014; Dodson et al., 2020). No relationship was found by Mathalon and Hill (2014) between MP (fibres) and sediment grain size. Dodson et al. (2020) concluded "it seems that sediment composition does not control microplastic distribution in our area" and the authors referred to a number of other studies where MP occurs independently of sediment type.

In order to explore for relationships between MP and total organic carbon content (TOC), papers were reviewed to search for any analyses of organic carbon content. None of the 16 papers on MP in beaches reported on TOC analyses.

The size distribution of MP particles is important for understanding

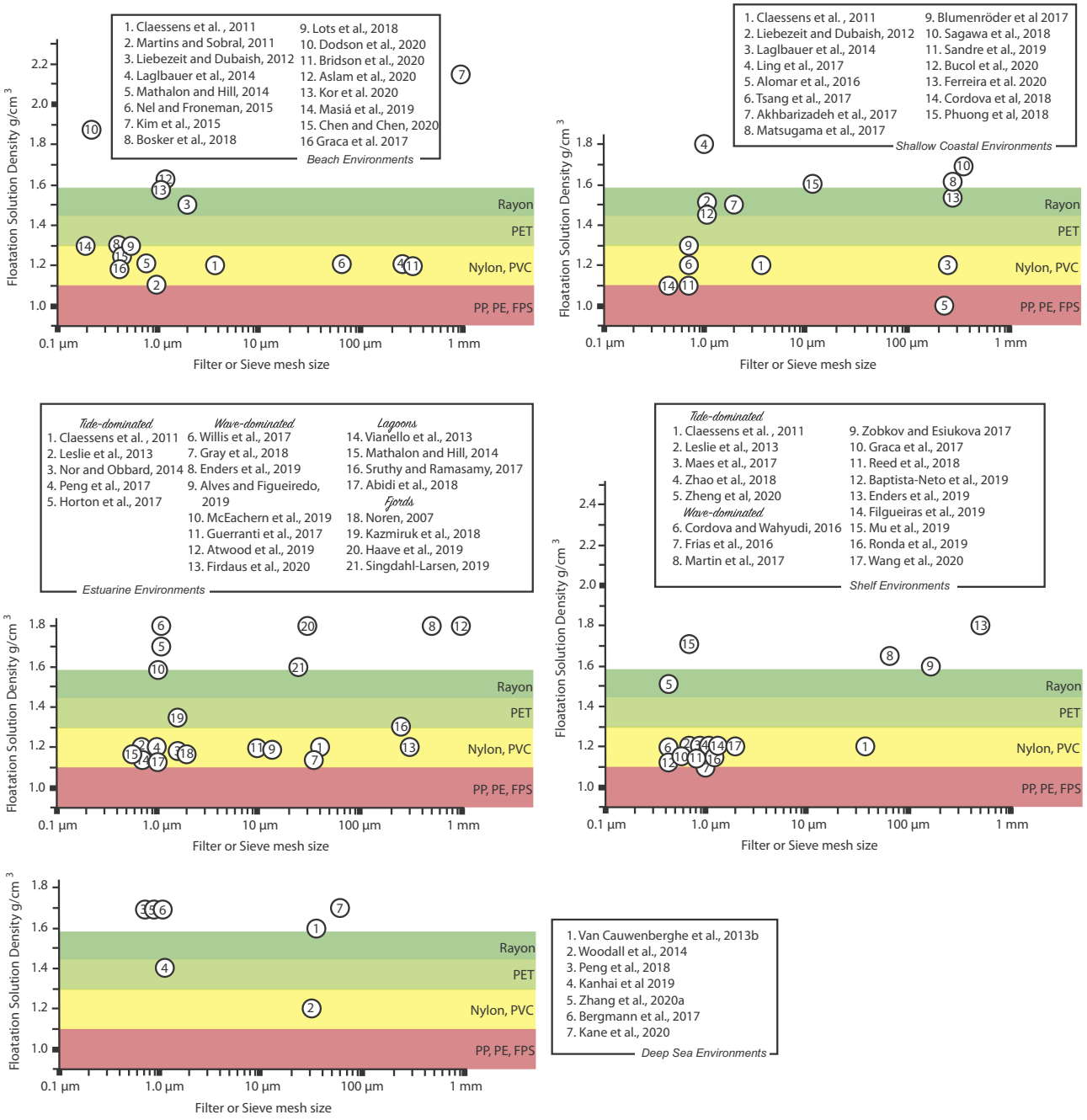


Fig. 6. Plots of density of liquid used to separate MP from sediment versus the log of the mesh size of the sieve or filter paper used to extract MP from the supernatant. The densities of some common plastics are indicated by the coloured bars: red is for polypropylene (PP), polyethylene (PE) and foamed polystyrene (FPS); yellow is for nylon and polyvinyl chloride (PVC); green is for polyethylene terephthalate (PET) and rayon. Studies where the density of the liquid was < 1.1 g/cm^3 plot in the red-shaded region, indicating the density below which most plastics will not float. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

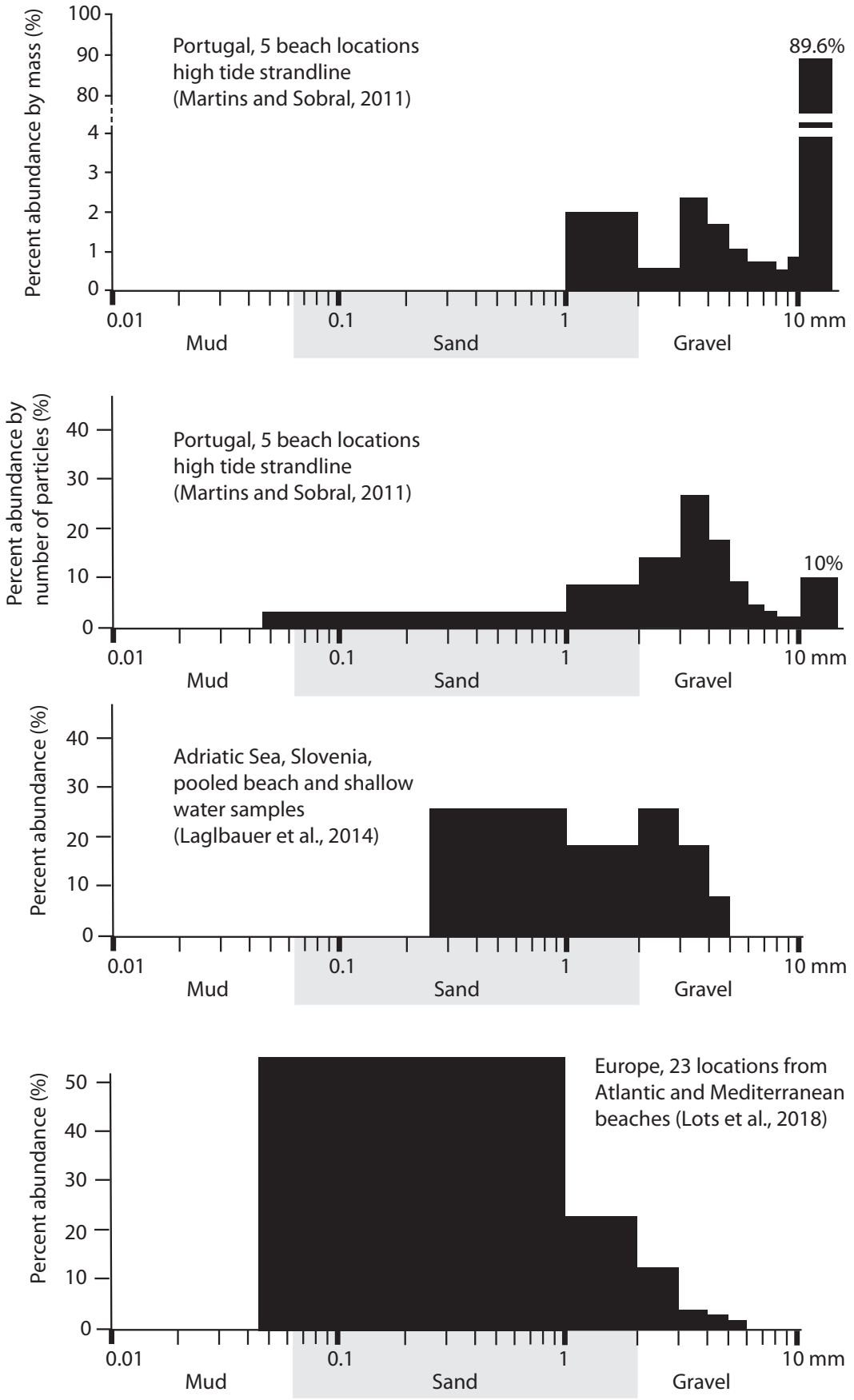


Fig. 7. Frequency distribution plots of MP size for beach case studies. The authors for each study are indicated. All data have been converted to log plots to enable comparison.

their transport and dispersal in the marine environment by currents and waves in relation to their hydraulic equivalence to natural sediment particles. The distribution of MP particle sizes can reveal information on its origin and history, as in the case of any natural sediment. In their study of beaches in Portugal, Martins and Sobral (2011) measured particle sizes in 11 classes from 50 μm to 200 mm (sand and gravel; Fig. 7) and found a modal peak at 4 mm (27% of particles). These authors also investigated the mass of plastic in each size class, finding that the 10% of particles larger than 10 mm accounted for 89.6% of total mass (Fig. 7). The study of Martins and Sobral (2011) was one of three papers reviewed here that reported the mass of MP extracted from different size classes. It is standard practice in sedimentology to report particle size frequency distributions in terms of the mass per size class, rather than the number of particles per size class which is the common practice among papers reviewed here; this is discussed further below.

In their study of Adriatic Sea beaches in Slovenia, Laglbauer et al. (2014) measured MP sizes in 5 sieve classes and found peaks in the > 250 μm to 1 mm and 2–3 mm size classes (Fig. 7), dominated by fibres. This bimodal distribution could indicate two different sources or types of MP (e.g. fibres versus fragments) but this was not discussed by the authors. The MP size distribution is also a combination of beach and subtidal sample data and differences in median sizes were found among the 6 different sample locations (Laglbauer et al., 2014).

Lots et al. (2017) measured particle sizes in 6 classes between 1 and 5 mm in their study of 23 locations from Atlantic and Mediterranean European beaches, and found a positively skewed distribution with 55% of particles in the < 1 mm size class, dominated by fibres. This skewed distribution (Fig. 7) requires greater resolution of size partitioning in the finer size fraction in order to resolve any modal peaks in the < 1 mm size class.

Browne et al. (2011) describe an increase in the numerical abundance of MPs with decrease in particle size (negatively skewed distribution). Kor et al. (2020) reported MP size distributions in 4 size classes from 100 μm to 5 mm; they found size classes of 100–500 and 500–1000 μm were the most abundant.

3.2. Microplastic in shallow coastal environments

For shallow coastal environments, 18 studies (17 papers) are included in this review. The studies are from intertidal to shallow water depths in embayments and along coastlines protected from the open ocean. In terms of the lowest MP concentration reported from shallow coastal environments, three studies (Laglbauer et al., 2014; Sandre et al., 2019; Ferreira et al., 2020) reported at least one replicate sample where MP was not detected. The maximum value of MP concentration reported is from tidal flats in the German Wadden Sea, where Liebezeit and Dubaish (2012) reported concentrations of up to18,600 particles kg^{-1}. Average numbers of particles kg^{-1} dry weight of sediment reported in the studies span 5 orders of magnitude, ranging from 3 particles kg^{-1} (Wessel et al., 2016) to 11,600 particles kg^{-1} (Liebezeit and Dubaish, 2012) with a median value of 200 particles kg^{-1} (Fig. 4).

Most of the 12 studies that reported MP types identified fibres as the most common form, but the median number of MP that are fibres was 60% (compared with 90% for beaches; Fig. 5). Four studies reported that fibres accounted for < 10% of MP. For example, in their study of bottom sediments of Hiroshima Bay, Japan, sampled at 18–35 m water depth, Sagawa et al. (2018) reported the occurrence of large numbers of foamed polystyrene (FPS) particles and only traces of fibres.

Out of the 17 separate papers on shallow coastal environments, only two did not use the floatation method to separate MP from sediments. Fok and Cheung (2015) identified MP directly after sieving the sediment at 315 μm, whereas Wessel et al. (2016) used a pneumatic flow method to separate MP from sediment.

The studies that did use the floatation method exhibit a broad range of fluid densities. Alomar et al. (2016) used only distilled water in their floatation methodology which means any MP having a density > 1.0 g/cm^3 is likely to not have been included in their assessment of MP concentration (Fig. 6). Seven studies used NaCl solution ranging in density from 1.14 g/cm^3 to 1.3 g/cm^3. Liebezeit and Dubaish (2012) and Bucol et al. (2020) used a $ZnCl_2$ solution (1.5 g/cm^3) whereas Matsuguma et al. (2017) and Sagawa et al. (2018) used a NaI solution (1.5 to 1.7 g/cm^3). Akhbarizadeh et al. (2017) used a two-step process of saline solution (1.2 g/cm^3) followed by NaI solution (1.6 g/cm^3). Sieving and/or filtering of the supernatant containing the concentrated MP varied widely among the studies. Five studies sieved the supernatant at coarser than 200 μm while the other studies mainly used small-sized filters (0.7 to 1.2 μm) to filter the supernatant (Fig. 6).

The studies by Ling et al. (2017), Akhbarizadeh et al. (2017) and Alomar et al. (2016) collected sediment grain size data. Alomar et al. (2016) measured sediment size by sieve analysis in 5 size classes and reported that there was no clear trend between sediment grain size and MP deposition. In their study of polluted sediment near the Kark Island oil terminal in Iran, Akhbarizadeh et al. (2017) measured sediment size by hydrometer; they did not mention if MP concentration correlated with grain size. Ling et al. (2017) measured sediment size by sieve analysis in 8 size classes and found different relationships for fibres (filaments) and MP fragments; wave exposure correlates with filaments, grain size with particles.

Akhbarizadeh et al. (2017) measured TOC content and found a correlation between it and grain size and that MPs correlate with heavy metals; they did not mention if there was any correlation between TOC and MP concentration. Ling et al. (2017) found a positive correlation between TOC and MP concentration.

MP size distribution was analysed in 5 of the papers included in this review (Fig. 8). The analysis of Adriatic Sea sediments in Slovenia by Laglbauer et al. (2014) was for pooled results from shallow infralittoral samples as well as for beaches already discussed above. In their study of various shallow coastal environments in southeastern Australia, Ling et al. (2017) measured MP in 7 size classes and reported separately for filaments and particles; a modal peak in size distribution for both filaments and particles occurs at around 100 μm. In their study of MP in fish and lower intertidal sediments sampled in the Negros Oriental, Philippines, Bucol et al. (2020) measured MP in 31 size classes and found the mean particle size to be 1367.69 μm ± 64.27, dominated by rayon fibres.

The study by Sagawa et al. (2018) compared MP concentration and particle size distribution in beach and the bottom sediments of Hiroshima harbour, Japan. As already mentioned, the MP was comprised almost entirely of foamed polystyrene (FPS) particles which were found to be more poorly sorted and to have a larger mean size (1.7–2.3 mm) compared with bottom sediment FPS particles (1.0–1.3 mm). The authors proposed that as FPS particles degrade on the beach they decrease in mean size and their pore spaces are infilled with silt and clay making them negatively buoyant.

3.3. Microplastic in estuarine environments

A total of 19 studies documented in 17 separate papers are included in this review of estuarine and deltaic environments. The study by Costa et al. (2011) reported several samples where MP was not detected; these authors sieved their samples at 1 mm and separated MP from sediment by visual identification to recover 38 MP items from 450 samples. Gray et al. (2018) found MP present in 98% of samples collected from two estuaries in South Carolina, USA; the other studies (16 out of 19) reported MP was detected in all samples. The maximum value of MP concentration reported is from a lagoon in Nova Scotia, Canada, where Mathalon and Hill (2014) reported 60 particles in one 10 g sediment sample (i.e. 6000 particles kg^{-1}).

Average numbers of particles kg^{-1} dry weight of sediment range from 3.5 (Costa et al., 2011) to 4100 particles kg^{-1} (Mathalon and Hill, 2014) and exhibit a median value of 300 particles kg^{-1}. Splitting estuarine environments into three categories (Fig. 4) indicates tide-

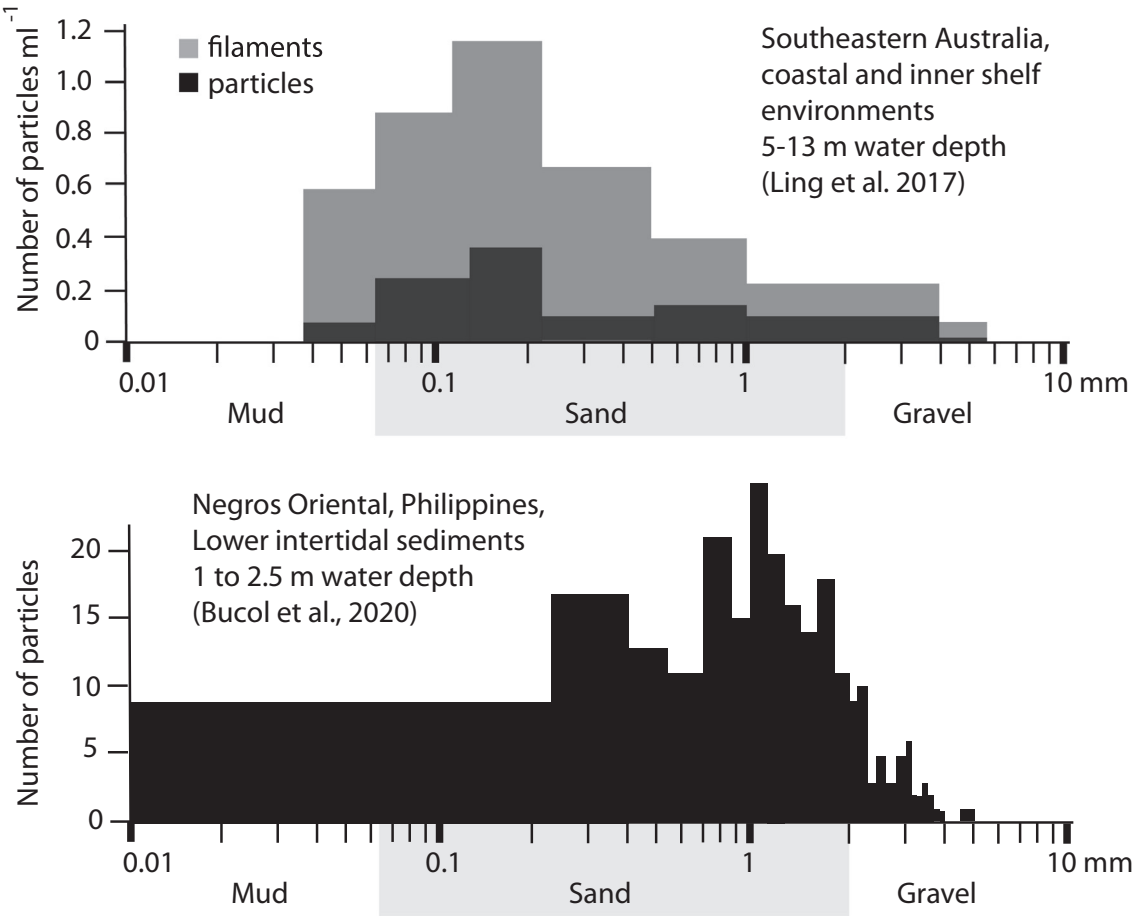


Fig. 8. Frequency distribution plots of MP size for shallow coastal environment case studies. The authors for each study are indicated.

dominated estuarine and deltaic environments exhibit a median value of ~150 MP particles kg^{-1}, wave-dominated estuarine and deltaic environments exhibit a median value of ~300 MP particles kg^{-1} and lagoon environments exhibit a median value of ~800 MP particles kg^{-1}. These values are consistent with sediment trapping efficiencies that are higher for lagoons and wave-dominated estuaries than for tide-dominated environments (Harris and Heap, 2003).

Fibres are identified as the most common form of MP in estuarine and deltaic environments, with the overall median value reported as 57% based on 11 studies. It is interesting to note that the 5 tide-dominated studies had a median of 47% fibres whereas the 4 wave-dominated estuaries and deltas had a median value of ~70% (Fig. 5). The two studies from lagoons that reported the percentage of fibres found highly contrasting values of 10% fibres in the Venice Lagoon (Vianello et al., 2013) versus 67% fibres in coastal lakes of Tunisia (Abidli et al., 2018).

Out of the 17 separate papers on shallow coastal environments, only that of Costa et al. (2011) did not use the floatation method to separate MP from sediments (Fig. 6). Seven studies used a fluid having a density > 1.6 g/cm^3 and none used a fluid with a density < 1.1 g/cm^3 (Fig. 6). Most of the studies used NaCl solution ($n = 13$), ranging in density from 1.16 g/cm^3 to 1.3 g/cm^3. Enders et al. (2019) used sodium polytungstate (1.8 g/cm^3), Willis et al. (2017) and McEachern et al. (2019) used NaI solution (1.6–1.8 g/cm^3) and Horton et al. (2017) used $ZnCl_2$ (1.7 g/cm^3). For sieving and/or filtering of the supernatant, the studies fall into three broad groups. One group is centred around a size of ~1 μm, a second group occurs in the 10–40 μm size range and the third group employed sieves > 200 μm in size (Fig. 6).

Only the study of Willis et al. (2017) measured sediment accumulation rates in relation to MP in the estuarine case studies reviewed here. These authors sampled MP in two core sites in the Derwent Estuary, Tasmania and found that the MP abundance decreases with depth down-core in both cores. Variations in the MP concentration were shown to be in concert with the rate of global plastic production. Fibres found lower in sediment cores, dated to 150 to 260 years ago, were seen as evidence of possible contamination of the cores (Willis et al., 2017).

Seven studies included the measurement of sediment grain size data in relation to MP concentration data and four studies found no statistically significant relationship between these variables (Nor and Obbard, 2014; Peng et al., 2017; Alves and Figueiredo, 2019; and Mathalon and Hill, 2014). On the other hand, Enders et al. (2019) found that some MP having density > 1 g/cm^3 correlates with sediment grain size, consistent with the result of Ling et al. (2017) that grain size correlates with concentration of MP particles but not with MP filaments (fibres). It is interesting to note that the four studies that found no relationship between grain size and MP concentration were studies that either focussed completely on fibres (Mathalon and Hill, 2014) or had ~90% or more of MP occurring as fibres.

TOC content was measured in 3 of the 19 studies reviewed here. In their study of the Warnow Estuary, Baltic Sea Coast, Germany, Enders et al. (2019) found that a correlation exists between the concentration of MP < 500 μm and TOC content. In their study of Rio de Janeiro Harbor, Guanabara Bay, Brazil, Alves and Figueiredo (2019) found no correlation between the concentration of MP and TOC content. In the Venice Lagoon, Italy, Vianello et al. (2013) described how MP tends to accumulate in low-dynamic areas, but the authors did not mention specifically if their data indicated any statistically significant relationship.

The MP size frequency distribution was measured in five studies (Fig. 9). In their study of estuarine mangroves in Singapore, Nor and

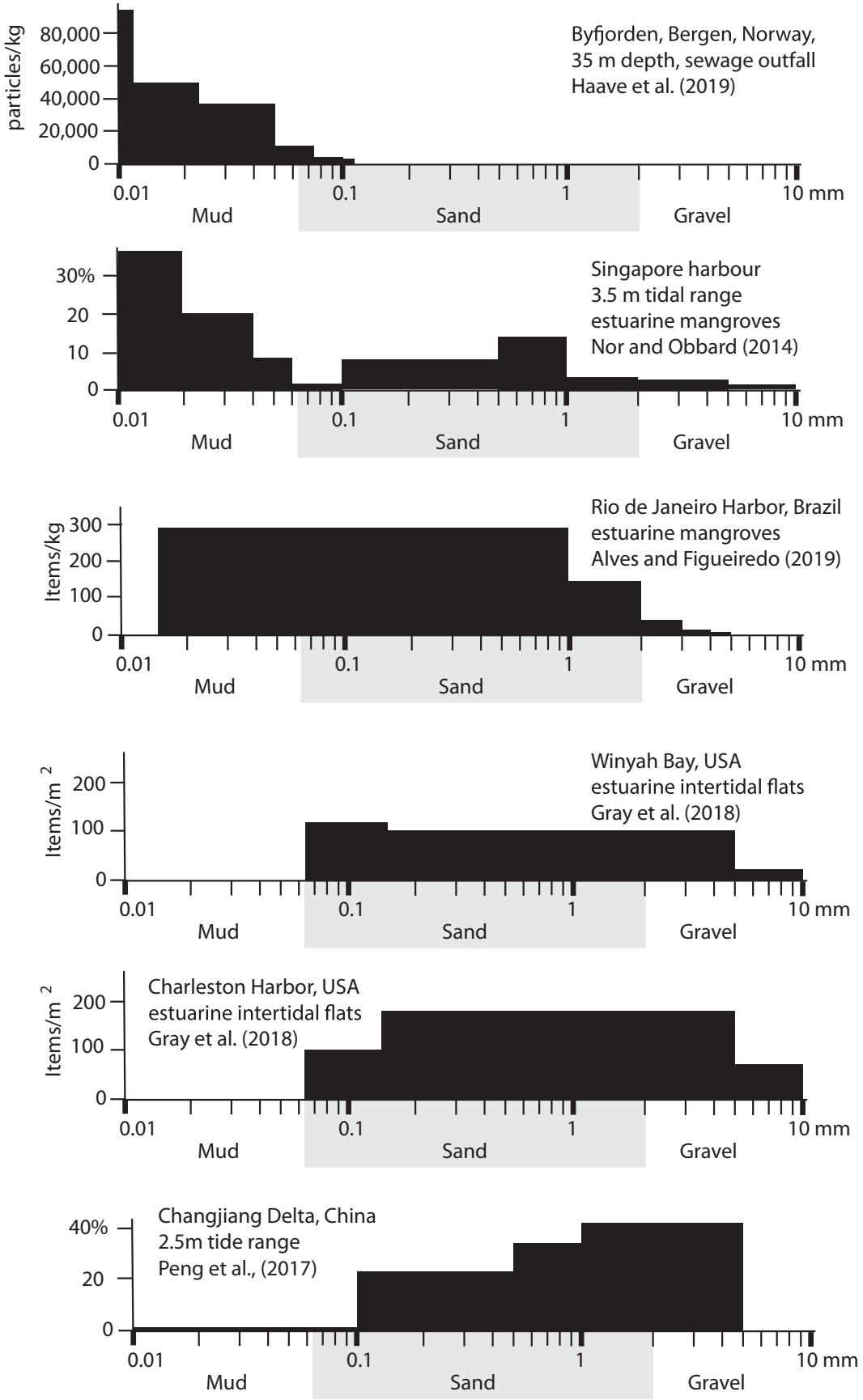


Fig. 9. Frequency distribution plots of MP size for estuarine and fjord environment case studies. The authors for each study are indicated.

Obbard (2014) measured MP in 10 size classes and found a bi-modal size distribution with one peak at around 1000 μm and a another peak in the < 20 μm size fraction (positive skewness) representing 37% of particles. Peng et al. (2017) assessed the MP size distribution in 53 box core samples collected in the outer Changjiang Delta, China, and found a negatively skewed distribution among 4 size categories with 42% of particles in the 1–5 mm category and only 1% in the < 100 μm category. In two wave-dominated estuaries on the USA east coast, Gray et al. (2018) collected samples from beach and intertidal zones along the estuary margins; the MP (mainly fragments) in three size classes studied showed a modal peak in the middle size class (150–500 μm) in Charleston Harbor and a positively skewed distribution in Winyah Bay (> 63 μm to < 150 μm size class). Lastly, in Rio de Janeiro Harbor (Guanabara Bay), Brazil, Alves and Figueiredo (2019) measured MP concentration in 5 size classes and found a positively skewed distribution with a peak in the smallest size category < 1 mm at all four locations studied.

3.4. Microplastic in fjord environments

A total of 5 studies (5 papers) are included in this review of fjord environments. No study reported a sample where MP was not detected and the maximum value of MP concentration reported is 200,000 particles kg^{-1} from the Byfjorden, Bergen, Norway reported by Haave et al. (2019); this is the highest concentration of MP reported by any study included in this review. Average numbers of particles kg^{-1} dry weight of sediment range from 190 to 77,000 particles kg^{-1} and exhibit a median of ~7000 particles kg^{-1} (Fig. 4). This median value is an order of magnitude greater than that for beaches, shallow coastal environments or other estuarine environments (Fig. 4).

The studies gave mixed results regarding the morphotype composition of MP, with reports of fibres, spheres and fragments all being the dominant form in different studies (Fig. 5). In a study of bottom sediments in Swedish industrial harbours, Noren (2007) found most particles were 0.5 to 1 mm diameter, milk-white to transparent spheres. Samples collected in shallow water near storm water outlets into Puget Sound, USA, showed the MP were mainly fibres according to Black et al. (2018). Haave et al. (2019) did not specifically state that the polyurethane acrylic resin that dominated MP < 500 μm sampled adjacent to sewage outfalls near Bergen, Norway, occurred in the form of "fragments" but they did note that it is "commonly used for paints and boat varnish", which would seem more likely to occur as fragments rather than fibres. In a study of sediments and core samples collected in the Oslo fjord, Singdahl-Larsen (2019) found that fibres were the dominant form of MP in the upper sediment layers (most recent MPs) but that other forms (films and fragments) dominated lower down in the cores in older sediments.

To separate MP from sediments by the floatation method, sodium chloride (NaCl) solution was used by Noren (2007) whereas Haave et al. (2019) and Singdahl-Larsen (2019) used zinc chloride ($ZnCl_2$). Black et al. (2018) wet-sieved their sediment samples at 1 mm and 335 μm and visually picked the MPs from the sieved sediment. For sieving and/or filtering of the supernatant, the studies of Haave et al. (2019) and Singdahl-Larsen (2019) used ~30 μm sieves whereas Noren (2007) used a 2 μm filter and Kazmiruk et al. (2018) used a 1.2 μm filter (Fig. 6).

Singdahl-Larsen (2019) measured sediment accumulation rates in relation to MP sampled in two core sites in the Oslo fjord, Norway. The cores indicate a decrease in MP concentration in recent years from a sub-surface maximum of 106,745 particles kg^{-1} dated from before 1950. The decrease in MP is attributed to improved waste management systems being in place in recent decades.

Haave et al. (2019) measured the sediment grain size and TOC content in 4 surface sediment grab samples to investigate for possible correlations with MP concentration. These authors concluded that the highest concentrations of MP for particles < 500 μm in size matches TOC depositional areas as well as depositional areas of fine sediment grain size. These authors also measured MP in 22 size classes and found all samples to be highly positively skewed, whereby nearly all particles are < 50 μm and the single largest size category was the < 11 μm size category (Fig. 9).

3.5. Microplastic in continental shelf environments

A total of 19 studies (17 papers) are included in this review of continental shelf environments. The range in MP concentration measured extended from zero reported by 8 of the studies to a maximum value of 3146 particles kg^{-1} on the west European shelf by Maes et al. (2017). Average numbers of MP particles kg^{-1} dry weight for shelf environments range from 1.7 particles kg^{-1} in the Tyrrhenian Sea (Mistri et al., 2020) to 421 particles kg^{-1} (Maes et al., 2017) and exhibit a median value of ~50 particles kg^{-1}. Splitting shelf environments into two categories (Fig. 4) indicates tide-dominated shelves exhibit a median value of ~120 MP particles kg^{-1} and wave-dominated shelves exhibit a median value of ~30 MP particles kg^{-1}.

Fibres are identified as the most common form of MP in shelf environments, with the overall median value reported as ~64% based on 16 studies. The 4 tide-dominated shelf studies had a median of 64% fibres whereas the 12 wave-dominated shelf studies had a median value of ~70% (Fig. 5). Overall, fibres comprised > 50% of MP in 11 out of 16 shelf studies. Among those studies having abundance of fibres < 50%, Cordova and Wahyudi (2016) found mostly MP granules in samples from the Sumatra shelf, Maes et al. (2017) found 59% spheres in North Sea samples, Munari et al. (2017) found the numbers of films plus fragments to be greater than the number of fibres in the Ross Sea, Antarctica, and Baptista Neto et al. (2019) also found the numbers of films plus fragments to be greater than the number of fibres in the shelf sediments adjacent to Rio de Janeiro Harbor, Brazil.

To separate MP from sediments, the floatation method was used with dense solutions of various types, with NaCl used in 14 studies. Two studies that did not use the floatation method were Munari et al. (2017) study of Ross Sea, Antarctica and Mistri et al. (2020) study of shelf sediments in the Tyrrhenian Sea. Both of these studies sorted and sized MP visually under a microscope. Of the five different environments, shelf studies were the most consistent with 11 out of 17 studies using a liquid density of around 1.2 g/cm^3 and filter size of around 1 μm (Fig. 6).

Four shelf studies made reference to sediment accumulation rates. Martin et al. (2017) used radio carbon dating of shells taken from depths down core to infer sediment accumulation rates. The dates gave mixed results with MP occurring at depths down-core that should have pre-dated the invention of plastic. Enders et al. (2019) cited a sediment accumulation rate of 3 mm/year for their Baltic Sea study area in the context of sediment trap data that indicated an average of 37 particles m^{-2} $year^{-1}$ reaching the seafloor. Taken together, these figures match observations in which the upper layer of surface sediment contains on average 222 particles m^{-2} or 5 particles kg^{-1} of dry sediment (Enders et al., 2019). Zheng et al. (2020) cite an accumulation rate of 0.7 cm $year^{-1}$ for Jiaozhou Bay in China and used their measurements of MP mass from 5 sediment cores to estimate the likely total mass of plastic deposited in the bay to be 3.71 tonnes. Graca et al. (2017) referenced a sediment accumulation rate in the Gdansk Deep of 1.6 mm $year^{-1}$ to conclude that the top 1 cm sediment surface layer was deposited over the last 5–6 years.

Two shelf studies found that MP concentration correlates with grain size (Maes et al., 2017; Mu et al., 2019) and three studies found no correlation (Filgueiras et al., 2019; Ronda et al., 2019; Wang et al., 2020). Zheng et al. (2020) reported that average MP size correlates with average sediment size whereas Zobkov and Esiukova (2017) found that MP concentration (fragments + films) increased with sediment sorting. For those 4 studies that measured sediment TOC, Maes et al. (2017) found a correlation with MP whereas Mu et al. (2019) and

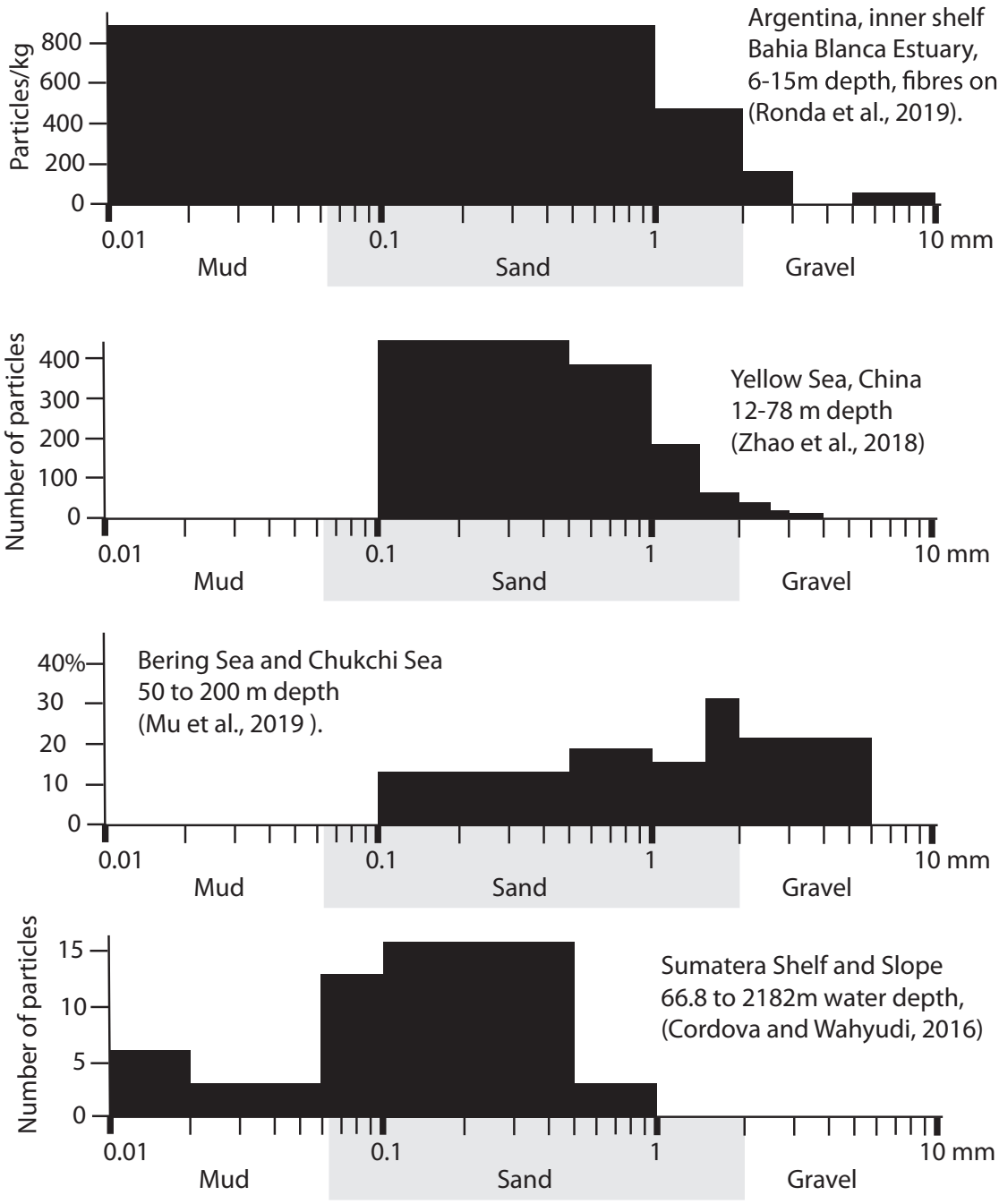


Fig. 10. Frequency distribution plots of MP size for shelf case studies. The authors for each study are indicated. Note different units used on vertical axes.

Ronda et al. (2019) did not. Enders et al. (2019) found that a correlation exists between small MP < 500 μm and TOC content.

The MP size frequency distribution was measured in 7 studies (5 authors; Fig. 10). In their study of the Sumatra shelf, Cordova and Wahyudi (2016) collected 41 MP particles and placed them into 5 size classes and found highest occurrence in the 100–500 μm size class (Fig. 10). The MP size distribution in sediments from the Bering and Chukchi Seas measured by Mu et al. (2019) exhibits a normal distribution with a mean size of 1.63 ± 1.12 mm. Zhao et al. (2018) pooled their data from the Bohai Sea, Northern Yellow Sea and Southern Yellow Sea into 10 size classes from 1 μm to 5 mm; the result was a positively skewed distribution with mean size of 854.88 ± 698.6 μm. Ronda et al. (2019) measured MP fibre numbers in six size classes and found a positively skewed distribution with and average size of 0.97 mm (Fig. 10). Filgueiras et al. (2019) measured MP numbers in four size classes (< 0.5 mm; 0.5–1 mm; 1–2 mm and 2–5 mm) for samples collected on the Spanish, Mediterranean shelf and found 61% of MP's in the 0.5 to 1 mm size class.

3.6. Microplastic in deep sea environments

A total of 14 studies (10 papers) are included in this review of deep sea environments. MP was found to be absent in some samples collected in three case studies. Five particles were found by Van Cauwenberghe et al. (2013b), one each in 5 out of 11 core top samples examined from three separate regions: a) the Nile Fan in 1176 m water depth; b) the Porcupine Abyssal Plain, North Atlantic, 4800 m; and c) the South Atlantic abyssal plain, 2700 m. In their study of the Arctic Ocean, central basin, 855–4353 m water depth, Kanhai et al. (2019) found MP in 7 out of 11 sites examined. On the Western Pacific Abyssal plain in

4601 m to 5732 m water depth, D. Zhang et al. (2020) collected MP in 13 out of 15 box core samples.

A maximum value of 13,331 particles kg^{-1} was reported for the Arctic Ocean Hausgarten observatory by Tekman et al. (2020). Kane et al. (2020) reported a concentration of 191 particles (182 fibres and 9 fragments) from one 50 mg box core sample 1 cm^2 by 5 cm in depth; this measurement is converted here to 3820 particles kg^{-1}. The difference in units points to a larger problem of inconsistencies with the way MP measurements are reported and interpreted in the literature (GESAMP, 2016; Hanvey et al., 2017).

An understanding of mean MP particles kg^{-1} for deep sea environments is challenging due to the small number of published studies. The values plotted on Fig. 4 include the observation of 1 particle found in each of 5 separate core tops by Van Cauwenberghe et al. (2013b), interpreted here as < 1 MP particle kg^{-1}. At the opposite end of the spectrum we have the Arctic Ocean Hausgarten observatory studied in two papers by Bergmann et al. (2017) who reported an average of 4356 ± 675 particles kg^{-1} and Tekman et al. (2020) who reported an average of 4730 ± 5107 particles kg^{-1} (for the same geographic area); a single average value (4543) is shown in Fig. 4. From the average MP concentrations reported in 9 deep sea studies, the median value is ~80 particles kg^{-1}. Fibres were the dominant MP morphotype reported in 7 studies with a median value of 75% (Fig. 5).

To separate MP from sediments, the floatation method was generally used with liquids of various densities (Fig. 6). Exceptions were the study of Fischer et al. (2015) who sieved their samples (minimum size 300 μm) and visually identified MP in the sediment using a microscope, and Courtene-Jones et al. (2020) who used an oil extraction method which is not density-based but rather takes advantage of the oleophilic properties of microplastics. The size of sieves and filters used on the supernatant to extract MP ranged from 0.7 μm to 53 μm (Fig. 6). Bergmann et al. (2017) and Tekman et al. (2020) used a specialized Munich Plastic Sediment Separator (MPSS) system (Imhof et al., 2012) which is reportedly highly efficient in extracting small MP (< 1 mm).

The only deep sea study to measure sedimentation/accumulation rate was that of Courtene-Jones et al. (2020) who employed ^{210}Pb to measure sedimentation rates (~0.02 g cm^2 $year^{-1}$) and sediment accumulation rates (0.04 cm $year^{-1}$ = 25 years/cm). MP decreased in concentration with depth down-core but MP was found at 10 cm depth down-core, corresponding to an age of ~200 years, well before the mass production of plastics. Mixing of the MP downward into the sediment via bioturbation is an obvious explanation (Näkki et al., 2017), but the sediment did not appear to be bioturbated. Courtene-Jones et al. (2020) propose instead that MP may be transported through sediments via pore water, a hypothesis which is supported by a positive correlation found between MP abundance and sediment porosity.

As for relationships between TOC and the concentration of MP in sediments, no relationship was found by Courtene-Jones et al. (2020). However Bergmann et al. (2017) and Tekman et al. (2020) reported that MP concentration correlates with Chlorophyll-A and particulate organic carbon POC at Arctic Ocean Hausgarten observatory stations. The relationship is explained by these authors as possibly being the result of the flocculation of algae incorporating MP along with it during its descent through the water column to the seabed.

The measurement of MP particle size frequency distribution was performed only in two studies (Fig. 10). Courtene-Jones et al. (2020) measured MP abundance in 16 size classes from < 0.5 to > 6.5 mm and found a negatively skewed distribution with a peak in the 0.5–1.0 mm size class. These authors used a 52 μm sieve to extract MP from floatation supernatant and noted they might have therefore underestimated MP abundance. Bergmann et al. (2017) measured 11 size classes from 11 to 275 μm and found a highly positively skewed distribution with the greatest abundance occurring in the smallest, 11 μm size class. The authors note that 80% of Hausgarten MPs were smaller than 25 μm.

4. Discussion

4.1. Most MP sourced from the land is "trapped" at the coast

The existing data on MP concentration in coastal and marine sedimentary environments indicate that the median concentration of MP is ~200 particles kg^{-1} dry sediment (DS) in beaches, ~200 particles kg^{-1} DS in shallow coastal environments, ~300 particles kg^{-1} DS in estuarine environments, ~7000 particles kg^{-1} DS in fjords, ~50 particles kg^{-1} DS on continental shelves and ~80 particles kg^{-1} DS for deep sea environments (Fig. 4). MP concentrations are thus between 4 and 140 times greater in estuaries and fjords than in shelf or deep sea environments. This result is consistent with observations made by previous workers: based on modelling work presented by Lebreton et al. (2019), Ritchie and Roser (2020) conclude that the "vast majority" of plastics that have entered the ocean since 1950, equal to 82 million tonnes of macroplastics and 40 million tonnes of MP, is "washed up, buried or resurfaced along the world's shorelines". Similarly, Wang et al. (2020), concluded that "sediments in enclosed waters capture microplastics and deposit them more easily".

Factors that will affect the estimation of the concentration of MP deposited in different environments include the sampling strategy: studies that seek out locations adjacent to sewage outfalls or locations most likely to contain MP pollution have been included in this assessment which have biased the results towards polluted coastal environments. Compounding this bias is the lack of reporting of negative results. No paper has been published on the absence of MP pollution in "pristine" environments, although it has been noted in the results above that at least one study reported at least one sample in which MP was not detected in beach, coastal and estuarine environments. Further from the coast, it is arguably more difficult to identify sites likely to be directly polluted from specific land-based sources and consequently we find that 8 of the 21 studies of shelf environments had at least one sample in which MP was not detected and 3 of the 13 deep sea studies had at least one sample in which MP was not detected. If studies report average values only for polluted sites and ignore negative results it will bias the assessment, again towards the more polluted sites.

Other important factors that will affect the estimation of the concentration of MP deposited in different environments that the present review has considered are: a) methodologies and the unit of measure for MP particles kg^{-1} dry sediment (DS); b) fibre MP morphotype versus other morphotypes; and c) sedimentary environment. These factors are discussed below.

4.2. Methodologies and units of measuring microplastics

The variety of methods used to measure MP concentration in marine sediments has produced results that are difficult to compare and which has hampered attempts to draw general conclusions about the fate of MP in the marine environment. Although the floatation method is most common, variations in the density of the liquid used as well as in the pore or mesh size of the filter or sieve used to extract MP from the supernatant (Fig. 6), together with variations in the techniques used to identify MP particles (i.e. visual identification, Raman spectroscopy, Fourier transform infrared microscopy μFT-IR, etc.; Löder and Gerdts, 2015) make the comparison of results problematic.

In order to advance our understanding of the fate of MP in different environments, the commonly used unit of measure for MP "particles kg^{-1} dry sediment (DS)" must also be questioned. Although this unit is often presented as a measure of MP "concentration" it is not in fact measuring concentration by mass (i.e. grams of MP per kg of dry sediment). The study of any quantity in ocean sciences (i.e. carbon, salts, oxygen, nutrients, etc.) measures fluxes and transport in units of mass rather than in the number of arbitrary "particles".

A major problem with counting particles is that they can be transformed from one state to another through the process of sample

collection and analysis. This is certainly the case with suspended sediment flocs, which are the main vehicle for the transport of organic matter from the water column to the seabed (Gibbs, 1985; Hill et al., 1998), but which are not recognisable once incorporated into seabed sediments. Laboratory procedures reported in the case studies reviewed here describe how the samples are sieved, dried, re-hydrated, centrifuged, stirred vigorously and (in two case studies) disaggregated by mortar and pestle. The number of MP "particles" is no doubt increased by such practices via mechanical fragmentation, which begs the question of how many "particles" were actually present in the sample in the first place. By contrast, the mass of MP is not impacted by sample collection or sample preparation laboratory procedures and is therefore a more robust measure. All MP studies are vulnerable to contamination, which is a recognised issue that has been considered already by a number of workers (e.g. Mathalon and Hill, 2014; Woodall et al., 2014; Willis et al., 2017; see also review by GESAMP, 2016) and could affect both MP mass or particle-count measurements, especially at low levels of MP content.

The estimated input of plastic to the ocean is reported in millions of tonnes/year and in order to discover where it is accumulating in the ocean and which habitats are most at risk, measurements of the concentration and rates of mass accumulation of MP are needed rather than estimates of the number of MP particles. Modelling of plastic dispersal in the ocean requires knowledge of both the source (input) and sink (output) terms and it is the case at present that many of these are poorly constrained (e.g., Law, 2017; Koelmans et al., 2017; Lebreton et al., 2019). The present study has focussed on understanding the amount of plastic entering the ocean sourced from land that is trapped in the coastal zone, but it is clear that estimates of the sink terms for the coastal zone (i.e. g m^{-2} $year^{-1}$) are presently unknown for different coastal environments (beaches, estuaries, fjords, etc.). Measurements of mass accumulation rates are needed for the different sedimentary environments to constrain modelling efforts.

Unfortunately, very few studies have collected MP mass data; Claessens et al. (2011), Martins and Sobral (2011) and Aslam et al. (2020) are the only studies reviewed here that did report MP in both g kg^{-1} DW and particles kg^{-1} DW. The data from Claessens et al. (2011) and Aslam et al. (2020) were analysed here by linear regression that demonstrated correlations (R^2) between g kg^{-1} DW and particles kg^{-1} DW are 0.53 and 0.0027, respectively (Fig. 12). These results show that simple empirical conversion from one unit to the other is not feasible; measurements of MP mass must be made directly.

Particle size frequency distribution plots of the data of Martins and Sobral (2011) for both mass and numbers of particles illustrate the complex relationship between particle size distribution and particle mass versus number of particles (Fig. 7). The two plots show completely different results: the plot of size frequency by mass exhibits two modal peaks at 1–2 mm and 3–4 mm with nearly 90% of the MP in the > 10 mm size fraction. By contrast, the plot of size frequency by number of particles exhibits one modal peak at 3–4 mm with only 10% of the MP in the > 10 mm size fraction. Thus, large numbers of very small particles in size frequency distributions based on particles kg^{-1} can be misleading. Peaks in the smaller size fractions are not necessarily an indication of higher mass concentration of MP. The data of Martins and Sobral (2011) show that a small number (10%) of large macro-plastic particles (> 10 mm in size) comprises the majority (89.6%) of the sample mass (Fig. 7).

In short, the number of particles kg^{-1} of sediment does not provide a quantitative measure of the fate of the mass of MP in the marine environment; data on MP flux rate (g m^{-2} $year^{-1}$) are required to make estimates of the mass of MP deposited and to calibrate models (Van Cauwenberghe et al., 2013a, 2013b). The number of particles kg^{-1} DW is an indication of where MP is present but this unit of measure does not provide the information needed to assess rates of MP mass accumulation in different sedimentary environments. These findings support the general conclusion of Law (2017) that "standardized sampling methodology and reporting are critically lacking in the detection, quantification, and characterization of plastic debris in the marine environment". Also the GESAMP (2019, p. 17) guidelines note that "selecting number or mass depends on both the policy question(s) being addressed and pragmatic concerns in producing reproducible and reliable data. Ideally both units would be used."

4.3. Mechanical fracturing of MP and particle size distribution

The Hjulstrom diagram (Fig. 1B) demonstrates how particles that are fractured and reduced in size during bedload transport results in particles around 1–4 mm in size (depending on density) before their size renders them unable to be transported as bedload, but only in suspension. If the process of fragmentation occurs predominantly via mechanical fracturing during bedload transport, it leads to the hypothesis that macroplastic particles will evolve towards MP particles in size distributions that exhibit modal peaks in the 1–4 mm size range (within populations of secondary MP particles). This is consistent with observations on coasts where most macroplastics (79%) are < 5 years old (Ritchie and Roser, 2020).

Examination of the 17 studies that provided MP size frequency distribution plots (Figs. 711) shows that 6 of them exhibit a modal peak in the 1–4 mm size range:

Martins and Sobral (2011) beaches in Portugal (Fig. 7);
Laglbauer et al. (2014) beaches of the Adriatic Sea coast of Slovenia (Fig. 7);
Bucol et al. (2020) intertidal sediments of Negros Oriental, Philippines (Fig. 8);
Gray et al. (2018) intertidal sediments Charleston Harbor (Fig. 9);
Peng et al. (2017) Changjiang Delta, 0–36 m water depth (Fig. 9);
Mu et al. (2019) Bering and Chukchi Sea continental shelf (Fig. 10).

These studies have in common shallow water and high-energy current/wave regimes and shallow beach and intertidal environments dominate. Martins and Sobral (2011) discuss several other examples of beach case studies that reported modal peaks of MP particle size in the 1–4 mm size range.

None of the MP size frequency distribution plots (Figs. 7–11) show only secondary MP (fragments) which is one explanation of why not all plots contain a modal peak in the 1–4 mm size range. Gray et al. (2018) was the only study out of the six listed above that noted a majority of particles were fragments (76.2%). The mixture of primary and secondary MP particles will obscure modal peaks of secondary MP particles where they comprise only a minor part of the population.

Another reason is that the MP size frequency distribution plots (Figs. 7–11) are based on numbers of particles and not on particle mass. As discussed above, this approach highlights modal peaks in small-sized, abundant particles over larger, more massive particles such as those occurring in the 1–4 mm size fraction. It is thus important to note that the majority of samples are dominated by small fibres (Figs. 5 and 7–11), which are expected to be transported mainly in suspension.

4.4. Fibres most abundant on beaches

MP fibres are the most common morphotype observed and exceed 50% of particles in 42 of 61 studies that reported MP morphotype (Fig. 5). Fibres are most common in beach environments with a median value of 90%, followed by deep sea environments (75%), wave-dominated estuaries and shelves (70%), tide-dominated shelf (63%), shallow coastal environments (61%) and fibres comprise only 49% of MP particles in tide-dominated estuarine systems (Fig. 5).

As discrete particles fibres are expected to behave quite differently in the ocean from fragments, pellets or granules of MP. This is because of their much greater surface area to mass ratio, which results in a low settling velocity (Khatmullina and Isachenko, 2017) which, in turn,

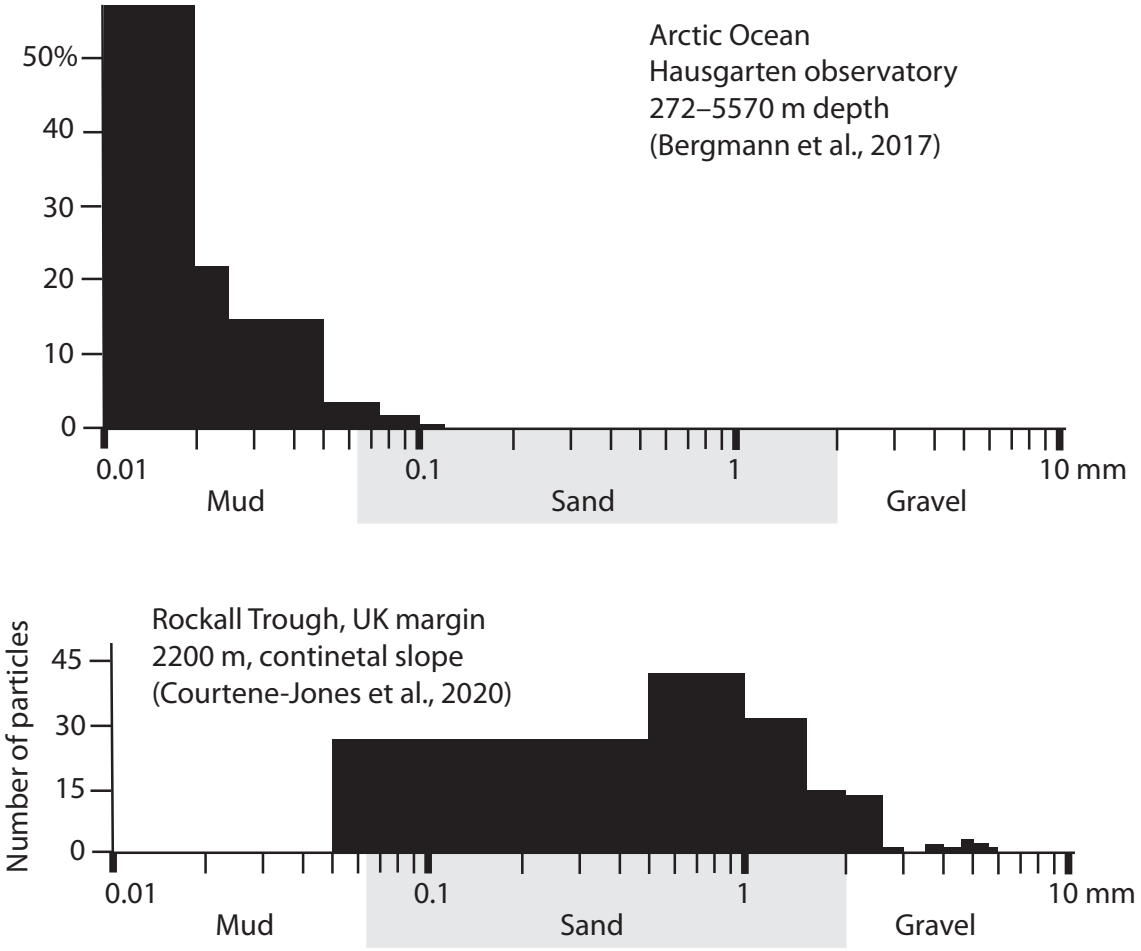


Fig. 11. Frequency distribution plots of MP size for two deep sea case studies. The authors for each study are indicated. Note different units used on vertical axes.

keeps them buoyant in the water column. This apparent enhanced buoyancy may explain the concentration of fibres on beaches which also receive other floating macroplastic debris (> 5 mm in size) and other more buoyant MP particles like FPS (e.g. Fok and Cheung, 2015; Kim et al., 2015; Sagawa et al., 2018).

The lower concentration of fibres in tide-dominated systems is probably associated with the lower sediment trapping efficiency commonly associated with these systems (Harris and Heap, 2003). Particles that remain in suspension (like MP fibres) are expelled from high energy tidal environments to be deposited elsewhere in adjacent coastal, shelf or deep water environments. Particles that rapidly sink to the seabed (like MP fragments) are more likely to be incorporated into estuarine deposits, such as on intertidal mudflats or the central muddy basins of wave-dominated estuaries and lagoons.

Apart from their enhanced buoyancy, another factor that could explain the higher concentration of fibres on beaches is that it is mainly fragments, as opposed to fibres, that are most commonly ingested by zooplankton (Md Amin et al., 2020). Thus the fibres are selected against for food by grazing plankton leaving them behind to be concentrated on beaches.

Once deposited on a beach, MP fibres may become incorporated into the sediment matrix through pore-water migration. The vertical movement of small fibres (occurring as silt or clay sized particles) through porous beach sediments via pore water has been suggested by earlier studies (e.g. Hidalgo-Ruz et al., 2012). In a similar way, Rusch et al. (2000) explained vertical profiles of particulate organic matter (POM) within permeable intertidal sediments to be a result of vertical transport via pore water. If fibres, rather than fragments, are preferentially trapped within porous beach sands through pore-water migration, this could explain their relative abundance in this environment (Fig. 5).

Beaches are also highly dynamic environments, subject to seasonal changes (winter/summer beach profiles). The occurrence of MP at depth in beach sediments noted by some studies (e.g. Turra et al., 2014; Graca et al., 2017) could also be related to seasonal beach dynamics as well as (or instead of) transport via pore water.

4.5. Sedimentary environments – the fate of plastic pollution

All plastic that enters the ocean will eventually be deposited on the seabed and become part of the sedimentary record. Experiments by Fazey and Ryan (2016) demonstrate that plastics less dense than seawater will eventually sink due to biofouling, with smaller particles sinking faster and after less time than larger ones (see also Kowalski et al., 2016). Koelmans et al. (2017) estimate that if the input of plastic to the ocean were stopped, most plastic particles would sink to the seafloor within 3 years. However, observations of decade-old macroplastics floating at sea challenge this view of a rapid cleansing of the surface ocean (Ritchie and Roser, 2020). Suffice it to say that given enough time, all plastic will be deposited.

The occurrence of plastic within the sediment column can be used as a tracer in the same way as radioactive tracers derived from atmospheric testing of nuclear bombs (e.g. Cesium-137). Sediments deposited prior to the 1950s should not contain any plastic and conversely, sediments that contain plastic must have been deposited after the 1950s. Sedimentary strata enriched in plastic are not only the geologic marker beds for the onset of the so-called “Anthropocene” (Crutzen and Stoermer, 2000), MP particles provide a tool for the study

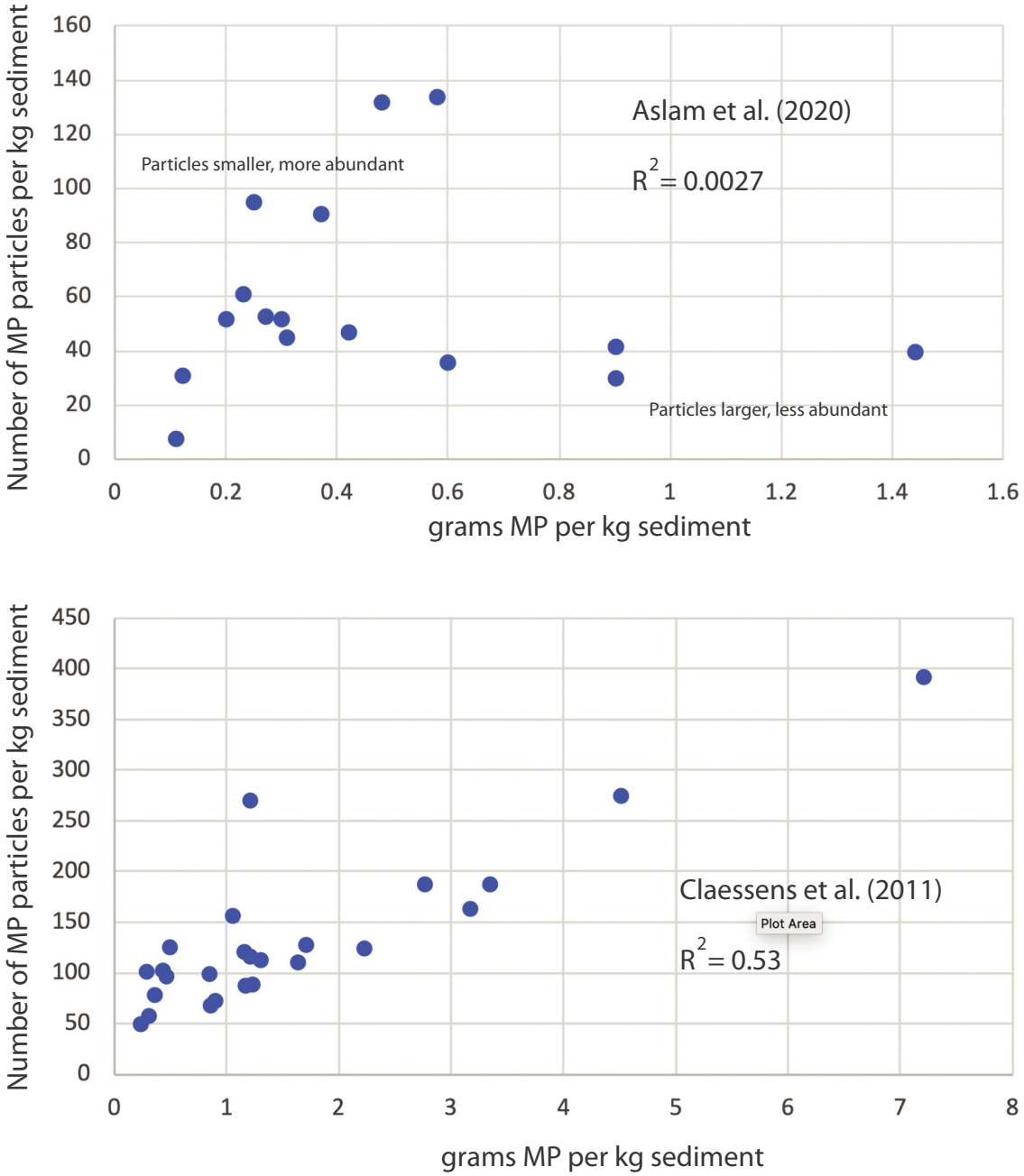


Fig. 12. Scatter plots of MP in units of grams/kg versus number of particles kg^{-1} from studies of Claessens et al. (2011) and Aslam et al. (2020). Variance (R^2) for each plot is indicated. The plots illustrate how populations of MP are comprised of both smaller, more abundant particles and larger, less abundant particles.

of deep sea sedimentary deposits and processes. A good example is how Courtene-Jones et al. (2020) explained the occurrence of MP within sediments radiometrically dated to a time before the industrial production of plastic, in which these authors inferred that pore water migration of MP must have occurred within the sediments. It may be questioned if fibres found in Derwent Estuary sediment cores at levels dated to 150 to 260 years ago by Willis et al. (2017), are evidence of possible contamination of the cores as these authors suggest, or if it is further evidence of pore water transport of MP particles.

For environments characterised by slow sedimentation rates such as commonly occur on continental shelves and in the deep sea (for example Courtene-Jones et al., 2020, measured a sedimentation rate of 0.009–0.055 cm $year^{-1}$ in their study from 2200 m water depth in the Rockall Trough), the entire inventory of plastic is expected to occur in the top few centimetres of the sediment pile. By contrast, environments characterised by rapid sedimentation rates (i.e. measured in cm per year or decade), such as commonly occur in deltas, fjords and estuaries, the top few centimetres of sediment will contain only the most recently deposited plastic particles. It is common practice in the studies reviewed here for sediment samples to be taken from the top 5 cm, which could either represent the plastic deposited in the last 5 years if the sedimentation rate is 1 cm per year, or the last 50 years if the sedimentation rate is 1 mm per year. On average, it can be expected that measurements of MP concentration taken from the top 5 cm of sediment deposits in deltas, fjords, coastal bays and estuaries are diluted by higher rates of sedimentation. For example, Zheng et al. (2020) found MP particles in cores collected from Jiaozhou Bay, Yellow Sea, to a depth of 45 cm.

Unfortunately, only 9 out of the 93 studies (~10%) included here made any mention of sedimentation rate or discussed its potential

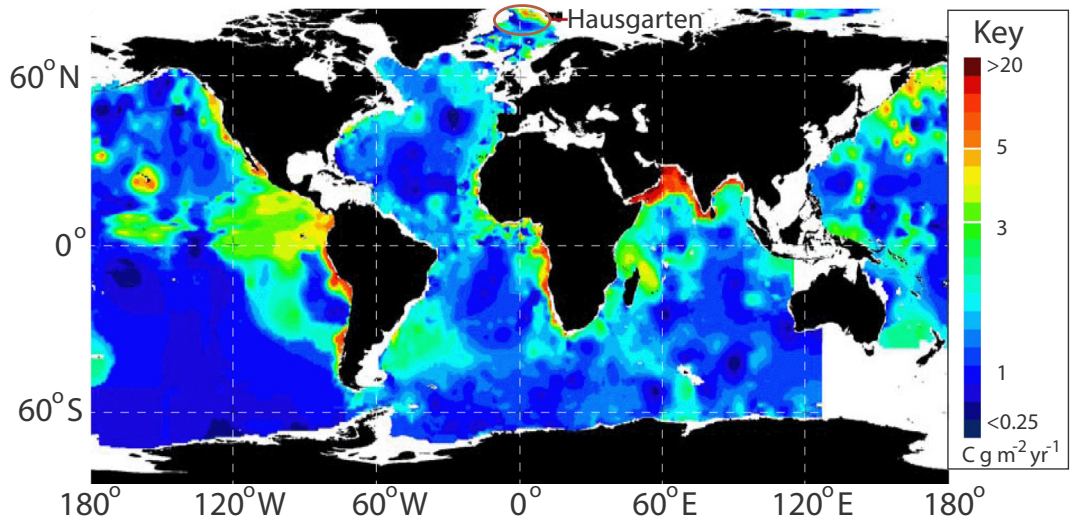


Fig. 13. Global POC flux to the seabed (modified from Seiter et al., 2005). Note the elevated POC flux that occurs in the region of the Arctic Ocean adjacent to Svalbard (red circle), which is the site of the Hausgarten observatory. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

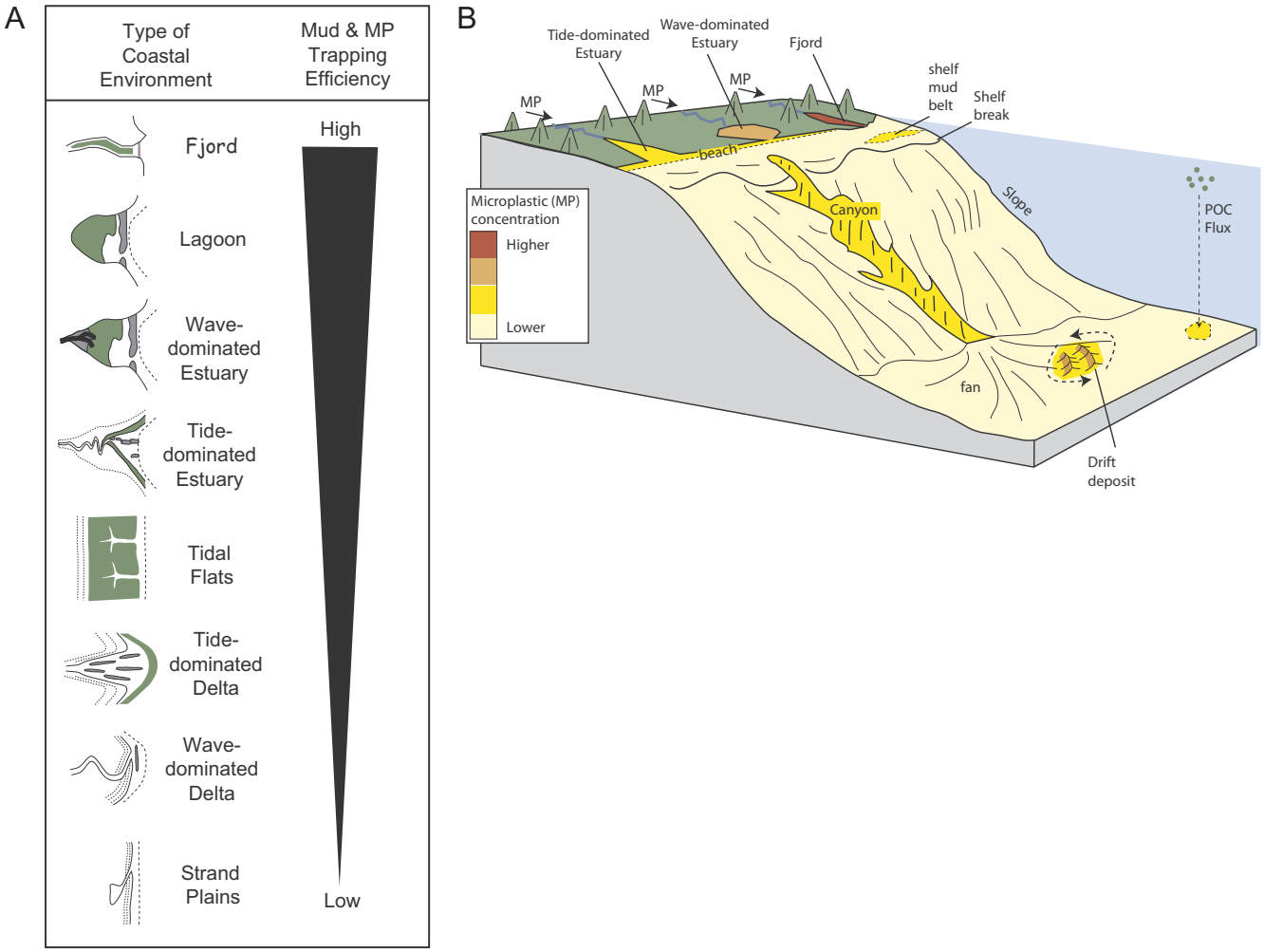


Fig. 14. Summary of sedimentary environments illustrating locations of greatest flux of MP into seafloor deposits as described in the text. A) Fjords have the highest MP trapping efficiency for fine sediment and MP; sandy beaches and strand plains have lower MP trapping efficiency. B) Shelf and deep sea environments have generally lower MP flux rates than coastal environments, but high rates may occur locally where bottom currents concentrate MP (e.g. on drift deposits, in submarine canyons and ocean trenches; Kane et al., 2020) or beneath locations of high POC flux driven by primary production (Tekman et al., 2020).

impact on the relative abundance of MP. Claessens et al. (2011) was the only study of MP on beaches that mentioned a sedimentation rate of 2–7 cm year^{-1}. Three studies from shallow coastal environments, estuaries and fjords (Matsuguma et al., 2017; Willis et al., 2017; Singdahl-Larsen, 2019) reported sedimentation rates of 0.3 to 0.5 cm year^{-1}, and four studies from continental shelf environments (Martin et al., 2017; Graca et al., 2017; Enders et al., 2019; Zheng et al., 2020) reported sedimentation rates of 0.002 to 0.7 cm year^{-1}. Equally important is information on coastal environments undergoing net erosion (coastal retreat), in which plastic particles may be re-introduced back into the environment after a period of temporary burial. Due to anthropogenic climate change, sea level is currently rising at around 0.3 cm year^{-1} which, when combined with other human impacts (.g. dam building, coastal armouring, mangrove deforestation, etc.), has caused the loss of 28,000 km^2 of land area between 1984 and 2015 (Mentaschi et al., 2018) and is expected to cause widespread coastal erosion in the 21st century and beyond.

To predict which environments are most likely to receive MP particles, proxies are sought such as TOC and sediment grain size. It is hypothesised that MP particles should be correlated with sediment TOC content, because organic matter and MP share some similar physical properties (e.g. density; Enders et al., 2019). Several authors have commented on the likelihood of a correlation between the fate of MP and organic matter in the marine environment. In fact only 15 out of the 80 papers reviewed here actually measured TOC content in association with assessment of MP content in sediments. Four papers that measured TOC did not follow up with a correlation analysis. Five papers reported there was no correlation between MP content (number of particles) and TOC% (Ling et al., 2017; Alves and Figueiredo, 2019; Mu et al., 2019; Ronda et al., 2019; Courtene-Jones et al., 2020).

Of the six papers that did find a relationship between MP content and TOC%, three papers noted that MP and particulate organic carbon (POC) both accumulate in low energy depositional environments (Vianello et al., 2013; Maes et al., 2017; Haave et al., 2019). Environments that appear to contain the lowest numbers of MP particles are high-energy, non-depositional sedimentary environments, such as rocky shores, high-energy (storm and tide-dominated) continental shelves paved with coarse sand and gravel, and tide-dominated estuaries that tend to export fine-grained sediment (Fig. 4). The highest numbers of MP particles occur in low-energy, depositional environments especially muddy, low-energy estuaries, fjords and lagoons that have the highest trapping efficiency for find sediment and MP.

The distribution of MP is heterogeneous in all environments (Fig. 4). It is evident that some coastal environments (e.g. beaches, estuaries, fjords, etc.) will contain higher concentrations of MP than others because they are closer to high population centres and thus exposed to greater amounts of pollution. However, the occurrence of locally high numbers of MP particles in remote, deep sea environments, far removed from any clear anthropogenic point source, must be explained by natural processes.

For example, continental slope sediment drift deposits are found to contain a higher concentration of MP than other deep sea environments. Kane et al. (2020) demonstrated through numerical modelling validated by bottom sediment sampling that MP is concentrated by bottom currents that transport particles into local depositional environments on drift deposits, whereas MP is depleted in other sites where bottom currents are eroding the seabed. It has been proposed by other workers that bottom currents may also concentrate MP into deep ocean trenches and submarine canyons (Ballent et al., 2013; Kane and Clare, 2019). Unless we find evidence of MP incorporated into turbidite beds, thus providing evidence that MP is transported down-slope into deep sea fan and drift deposits via hyperpycnal turbidity flows (e.g. Pohl et al., 2020), it seems that MP has thus far been recovered only from hemipelagic, surface-sediment drape deposits. This points to the mode of MP delivery to the deep sea is via dispersal as buoyant particles that eventually settle form the water column.

At the deep sea Arctic Ocean Hausgarten observatory, in a remote corner of the Arctic Ocean, Bergmann et al. (2017) and Tekman et al. (2020) found the highest concentrations of MP reported in the deep sea. What processes have caused this locally high concentration to occur? Bergmann et al. (2017) and Tekman et al. (2020) found that the concentration of MP correlates with Chlorophyll-A and POC content, which these authors explained as being driven by seasonal phytoplankton blooms. In this scenario, small MP particles (mainly fibres) are combined into sinking flocs of phytoplankton detritus that are exported to the ocean floor. The elevated concentration of MP at the Hausgarten observatory may thus be related to the high POC flux that naturally occurs in this part of the ocean (Fig. 13). If the occurrence of MP in ocean sediments is due to the same processes that control spatial variations in oceanic POC flux, then its spatial distribution may appear as in Fig. 13.

Considering MP as a passive tracer for understanding sedimentary processes promises to be a potentially rewarding line of investigation for future research. The vertical migration of MP within the sediment column via pore water has been discussed above, which has implications for understanding hydrocarbon reservoirs and radiocarbon dating of bulk organic carbon among other topics. Testing for the occurrence of MP within turbidites and other current-lain sedimentary units can reveal the relative age of such deposits and whether or not MP is being dispersed via bedload transport, by turbidites (e.g. Kane and Clare, 2019) or mainly by suspension load within different environments.

Sediment grain size is another proxy that might be expected to correlate with the occurrence of MP because fine-grained sediments are often found in low energy environments (where both POC and MP might be expected). Out of the 18 studies that considered sediment grain size, there were 9 studies that found no correlation and 9 studies that did. Where a correlation was found there were often some caveats: Enders et al. (2019) found that MP having a density > 1 g/cm^3 correlate with sediment grain size, whereas low density polymers did not correlate with grain size. Zobkov and Esiukova (2017) found that MP concentration (fragments + films) increased with sediment sorting. Ling et al. (2017) found that grain size correlates with MP particles but not with fibres.

These observations all point to a common explanation which involves different modes of MP transport. Correlations between sediment size and MP occurrence will exist in cases where MP particles are large and dense enough to be transported in bedload and are thus available to be hydraulically sorted along with sediment grains. For less dense MP particles (or fibre-shaped particles with a large surface area), transport is decoupled from sediments because such particles only settle to the seabed via biofouling, ingestion or some other mechanism. In such cases there is no relationship expected since the sediment and MP were delivered to the same location by different processes.

5. Summary and conclusions

From this review it is clear that MP particles share some important attributes of natural sediments. Their physical transport and dispersal into coastal environments follow similar pathways, with the most coarse-grained and dense particles deposited close to source. In high-energy, coastal and shelf environments, macroplastic items rapidly break down into smaller MP particles via mechanical fracturing during bedload transport. Finer, less dense particles that remain in suspension will settle to the seabed in low-energy environments that are efficient sediment traps (fjords, lagoons and wave-dominated estuaries; Fig. 14A).

In more energetic coastal settings, like tide-dominated estuaries and along wave-dominated coasts with strand plains, fine-grained particles may escape from the coastal zone and be transported offshore. Buoyant particles cross the continental shelf to be dispersed by ocean currents. Even the smallest, most buoyant MP particles eventually sink to the seabed as a consequence of flocculation, biofouling or ingestion. In this

way, MP particles are dispersed widely over the ocean but appear to be spatially concentrated in specific deep sea environments, particularly in canyons, deep ocean trenches, sediment drift deposits and beneath surface water areas of high-productivity that export POC to the seafloor (Fig. 14B).

This review and synthesis of existing information has examined 93 case studies from 80 publications on the occurrence of MP in the context of their location within particular sedimentary environments. The following specific conclusions are drawn:

1. Coastal environments exhibit the highest concentrations of MP whereas shelf and deep sea environments exhibit lower concentrations.
2. To a first approximation, therefore, MP behaves like most other sedimentary particles in that it is mostly deposited close to its land-based source.
3. Due to their high surface area to volume ratio, fibre-shaped particles are buoyant and are concentrated on beaches where they comprise ~90% of MP.
4. In order to advance our understanding of the fate of MP in the marine environment, quantitative assessments are needed of MP flux rates (g m^{-2} $year^{-1}$). This requires combined measurements of MP mass concentration (g kg^{-1}) and sedimentation rate (g m^{-2} $year^{-1}$) analysed from the full spectrum of coastal environments
5. Assessments of MP should take into account the nature of the sedimentary environment in the experimental design; most studies have targeted sandy beaches instead of the most rapidly accumulating environments such as fjords, prograding fronts of deltas, central muddy basins of wave-dominated estuaries and lagoons among others.

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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