Environmental Pollution 182 (2013) 495–499

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Short communication

Microplastic pollution in deep-sea sediments

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ARTICLE INFO

Article history:
Received 1 July 2013
Received in revised form
5 August 2013
Accepted 20 August 2013

Keywords:
Microplastics
Deep sea
Sediment
Pollution

ABSTRACT

Microplastics are small plastic particles (<1 mm) originating from the degradation of larger plastic debris. These microplastics have been accumulating in the marine environment for decades and have been detected throughout the water column and in sublittoral and beach sediments worldwide. However, up to now, it has never been established whether microplastic presence in sediments is limited to accumulation hot spots such as the continental shelf, or whether they are also present in deep-sea sediments. Here we show, for the first time ever, that microplastics have indeed reached the most remote of marine environments: the deep sea. We found plastic particles sized in the micrometre range in deep-sea sediments collected at four locations representing different deep-sea habitats ranging in depth from 1100 to 5000 m. Our results demonstrate that microplastic pollution has spread throughout the world's seas and oceans, into the remote and largely unknown deep sea.

1. Introduction

The world's seas and oceans are subjected to different kinds of threats of which the accumulation of anthropogenic debris is a major and worldwide problem that has been an environmental concern for decades. Despite the increased international attention, the build-up of these materials in the environment is considered problematic due to the increasing global plastic production (280 million tons y^{-1} in 2011 (PlasticsEurope, 2012)) and the continuing improper disposal of plastic waste. In the last decade it has been demonstrated that in the marine environment such large plastic items will break up into smaller fragments (Andrady, 2011; Cole et al., 2011) with dimensions as small as a few micrometre, the so called microplastics. Moreover, additional sources of microplastics have been identified: microplastic particles present in cosmetics (Fendall and Sewell, 2009) and microplastic fibres from fabrics such as polyester and polyamide (Browne et al., 2011; Dubaish and Liebezeit, 2013) present in domestic wastewater are not retained during sewage treatment and can thus enter the marine environment.

Many authors have defined microplastics as particles smaller than 5 mm (Arthur et al., 2009), while others have set the upper size limit at 1 mm (Claessens et al., 2011). While the value of 5 mm is more commonly used, 1 mm is a more intuitive value (i.e. 'micro' refers to the micrometre range). Most plastic present in the marine environment fits these small size classes. For instance, plastic particles <1 mm accounted for 65% of all marine debris items collected on beaches in the Tamar Estuary (U.K.) (Browne et al., 2010). Because of these small dimensions, microplastics become available for ingestion by organisms commonly not affected by the larger marine debris. Short-term laboratory trails have shown that marine invertebrates, representing different feeding strategies, can ingest these microscopic plastic particles. Polychaetes, bivalves, echinoderms and copepods will all, in at least one life stage, take up microplastics from the environment (Cole et al., 2013; Graham and Thompson, 2009; Thompson et al., 2004; Ward and Shumway, 2004). Once ingested, these microplastics can either be eliminated through defecation or retained in the tissues of the exposed animals (called translocation) (Browne et al., 2008; von Moos et al., 2012). Since there is a data gap concerning chronic effects of microplastic exposure, the implications of microplastic contamination in the marine environment are, to date, unknown.

Microplastics have been reported in the water column and marine sediments worldwide (Claessens et al., 2011; Law et al., 2010; Moore et al., 2001; Thompson et al., 2004), from low, background concentrations of 3 particles m^{-3} in water (Doyle et al., 2011) and 8 particles kg^{-1} in sediment (Thompson et al., 2004), to very high, hot-spot concentrations of 102 000 particles m^{-3} in water (Norén and Naustvoll, 2010) and 621 000 particles kg^{-1} in sediments (Liebezeit and Dubaish, 2012). The observed sediment

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0269-7491/$ – see front matter © 2013 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.envpol.2013.08.013

Table 1
Details on sampling locations and sampling stations, including sample collection method.

Sampling location	Geographical location	Station number	Latitude (decimal)	Longitude (decimal)	Depth (m)	Sample collection
Polar front	Southern Ocean	1	53°0.67′S	10°3.00′E	4230	Multicorer
		2	51°59.98′S	7°59.99′W	2749	
		3	49°33.81′S	38°24.27′W	4881	
Porcupine Abyssal Plain	North Atlantic Ocean	1	48°49.60′N	16°29.68′W	4842	Multicorer
		2	48°49.77′N	16°28.90′W	4843	
		3	48°49.41′N	16°29.85′W	4844	
Distal lobe of Congo Canyon	Gulf of Guinea	1	6°25.20′S	5°29.40′W	4785	ROV Victor 6000
		2	6°25.20′S	5°29.40′W	4785	
		3	6°25.20′S	5°29.40′W	4785	
Nile Deep Sea Fan	Mediterranean Sea	1	32°22.9′N	31°43.13′E	1176	Multicorer
		2	32°22.9′N	31°43.13′E	1176	

concentrations all originate from sites located on the continental shelf. However, accumulation zones of floating plastic debris and associated microplastics, the so-called garbage patches, are located far from any continental margin. Hence, the question arises whether the degradation products of larger marine debris are present in deep-sea sediments as well, since surface particulate material can be rapidly exported to abyssal depths.

Here, we investigate the presence of microplastics in one of the most pristine of marine environments: the deep sea. To explore the hypothesis that microplastics have entered the deep sea, sediment samples from deep-sea locations worldwide were analysed for the presence of microplastics by means of a new and highly efficient extraction technique using a high density salt solution.

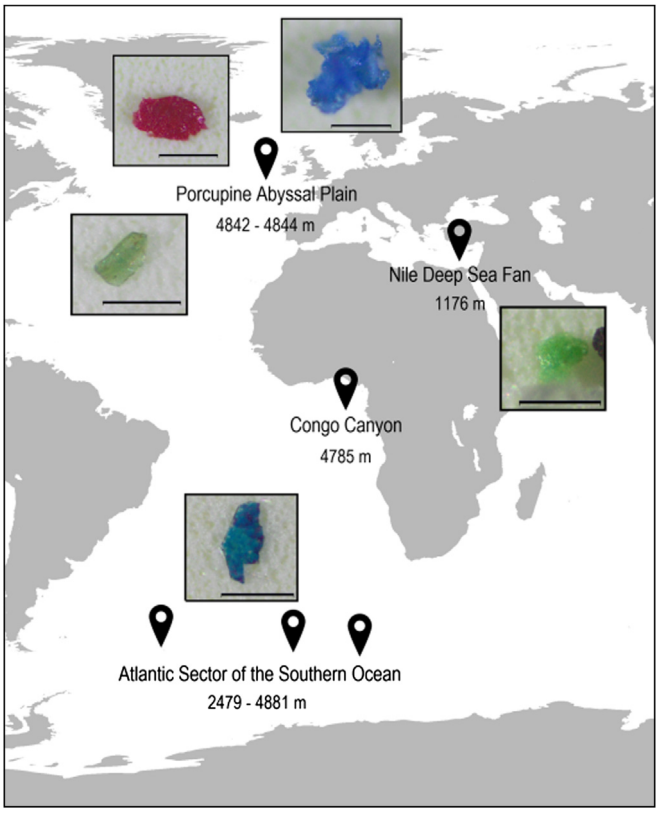

Fig. 1. Locations of the sites sampled and microplastics recovered from the deep sea sediments. Three locations in the Atlantic Ocean (Porcupine Abyssal Plain, Lobe of Congo Canyon and Atlantic sector of the Southern ocean) and one location in the Mediterranean Sea (Nile Deep Sea Fan) were sampled. Microplastics (see inserted photos) were detected in the top centimetre of sediments from three of the four sampled locations (Scale bar represents 100 μm).

2. Materials & methods

Microplastic extractions were performed on 11 sediments samples originating from several locations in the Atlantic Ocean and Mediterranean Sea ranging in depth from 1176 to 4844 m (see Table 1). These deep sea systems represent different marine environments. The three sampling stations in the Atlantic sector of the Southern Ocean, off the polar front were representative for a pristine environment, since the sea floor of this remote location is still largely unexplored and assumed void of pollution. In the Northern Atlantic Ocean, the Porcupine Abyssal Plain was sampled. This site is characterised by large seasonal variations in the flux of particulate organic matter (POM) derived from surface production (Lampitt et al., 2001). The distal lobe of the Congo Canyon (Gulf of Guinea, South Atlantic Ocean) is fuelled by organic matter delivered by one of the world's largest rivers, the Congo River (Khripounoff et al., 2003). The last sampling location is shallower and situated off the Nile Deep Sea Fan adjacent to the Amon Mud volcano in the Eastern Mediterranean Sea. This is an area on the Egyptian margin characterised by strong sedimentation, and influenced by the burial of thick accumulations of organic-rich sediments and the formation of hydrocarbons (Felden et al., 2013).

Each time a surface area of 25 cm^2 was sampled. Immediately after recovery, the cores were cut into horizontal slices by extruding it into a ring and slicing the sediment with a metal plate. The cores were cut into 1-cm-thick slices. Only the top centimetre of the sediment cores were analysed for the presence of microplastics. The extraction was performed according to Claessens et al. (2013), with minor modifications. Since the deep-sea sediment core samples represented only a small volume (25 cm^3), no volume reduction of the sample by elutriation was performed. Instead, sediment samples were wet sieved, first on a 1 mm mesh sieve and subsequently on a 35 μm mesh sieve. The fraction remaining on the 35 μm sieve was used for a further extraction based on density flotation using sodium iodide (density: 1.6 g cm^{-3}), as described in Claessens et al. (2013). The entire extraction process was performed with instruments that were rinsed with filtered deionised water (0.8 μm membrane filter, GelmanScience) and in a clean fume hood, in order to prevent contamination with airborne microplastics.

The particles that were classified as possible microplastics were analysed using micro-Raman spectroscopy. The spectra of the particles were recorded with a Bruker Optics 'Senterra' dispersive Raman spectrometer coupled with an Olympus BX51 microscope. The system used a thermoelectrically cooled charge-coupled device (CCD) detector. The instrument was controlled via the OPUS 6.5.6 software.

3. Results & discussion

In three of the four locations studied, microplastics were recovered from the top 1 cm of the sediment samples (see Fig. 1). In total, five particles were identified as possible microplastics: 1 particle originating from the Nile Deep Sea Fan, 1 from the Southern ocean, and three particles from the Porcupine Abyssal Plain. No

Table 2
Dimensions of the five microplastics recovered from the deep-sea sediment samples.

Sampling location	Depth (m)	Length (μm)	Width (μm)
Southern Ocean	2749	118	60
Nile Deep Sea Fan	1176	75	53
Porcupine Abyssal Plain	4842	161	137
Porcupine Abyssal Plain	4842	83	44
Porcupine Abyssal Plain	4843	125	76

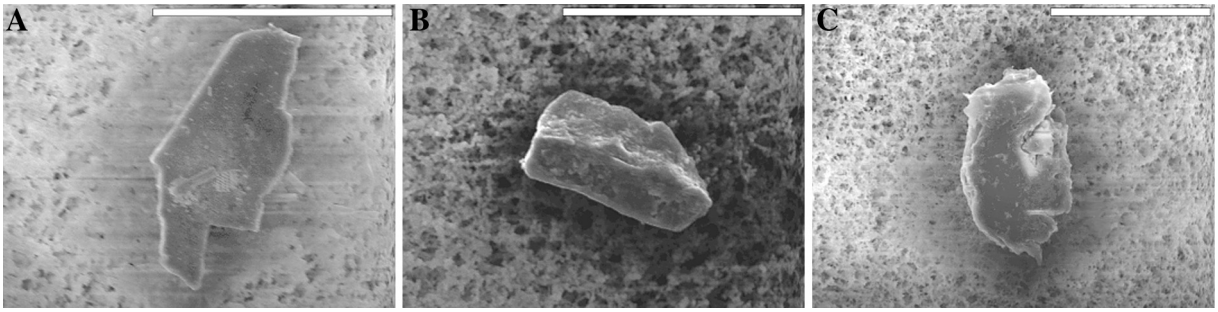

Fig. 2. Scanning electron microscopy images of microplastics. **A**. Blue particle extracted from sediment from the Southern ocean (2749 m). **B**. Green particle originating from the Porcupine Abyssal Pain (4842 m). **C**. Red particle extracted from sediment from the Porcupine Abyssal Plain (4843 m) (Scale bar represent 100 μm).

particles were recovered from the Congo Canyon. Based on the (limited) surface sampled it can tentatively be concluded that in/on the sea floor of the deep sea, microplastics can reach an average abundance of 0.5 microplastics per 25 cm^2 ($N = 11$) in the top centimetre of sediment. The highest concentration of microplastics was encountered in the sediment of the Porcupine Abyssal Plain: here, microplastics reached an average concentration of 1 particle per 25 cm^2 ($N = 3$). It is remarkable that no or limited numbers of

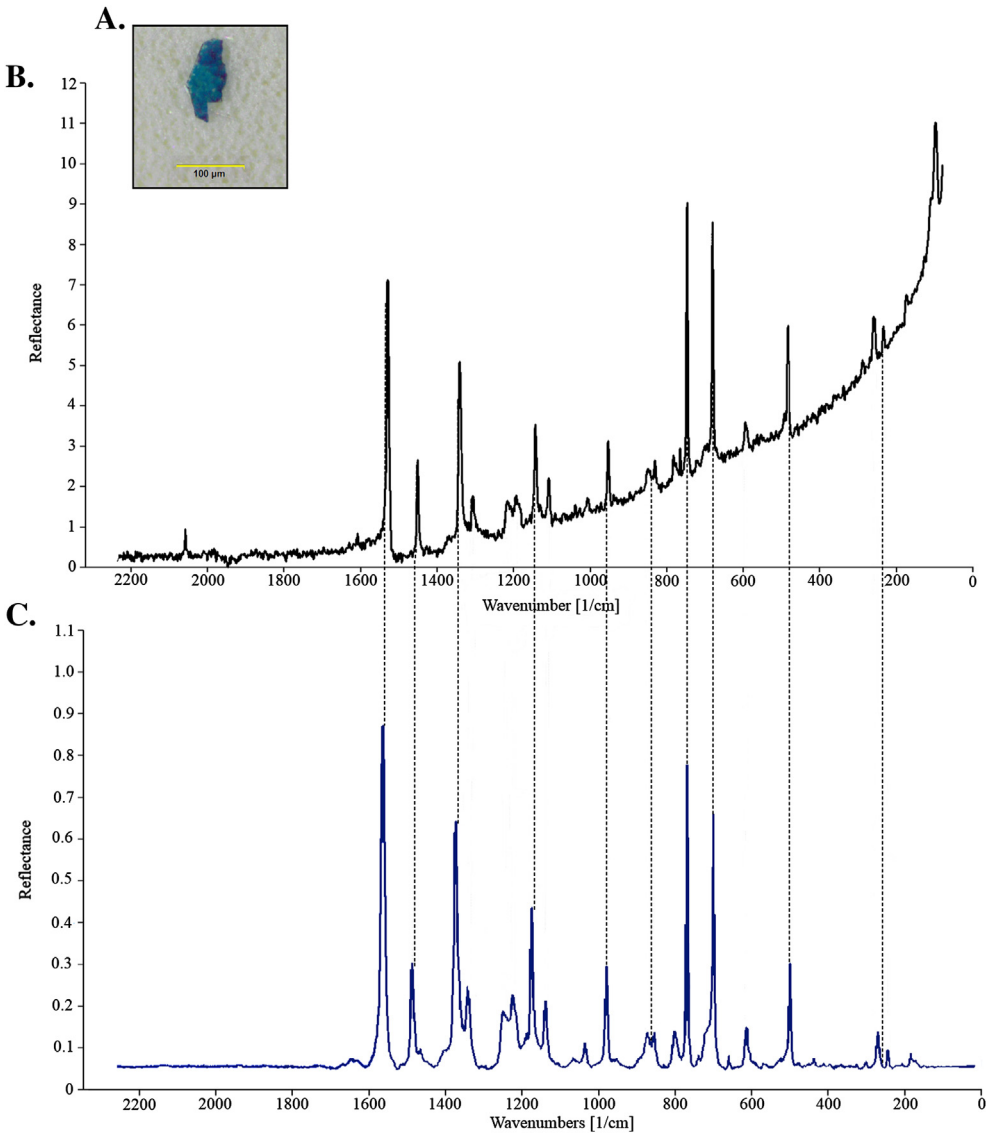

Fig. 3. Identification of microplastics using micro-Raman spectroscopy. **A**. Microplastic particle extracted from sediment originating from the Weddell Sea at 2749 m depth. **B**. Raman spectrum for the extracted particle. **C**. Raman spectrum for the widely used pigment copper phthalocyanine (blue pigment). The Raman peeks in this spectrum match with those represented in panel B (see dotted lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

microplastics were recovered from the location off the Congo and Nile rivers, since these rivers pass through countries that lack adequate waste management. Because of the small sample sizes (only two to three cores per location) and the small volumes per core, the fact that no microplastics were encountered does not imply that no microplastics were present at all. In addition, due to the high organic content of the samples originating from the Congo Canyon the filters contained high amounts of organic (plant) material that impeded the visual inspection for microplastics. It is thus possible that microplastics present in these samples were missed. The sampling stations in the Mediterranean are located near the edge of the Nile Delta Fan, where we would expect a reduced riverine input.

The characterisation of the extracted particles involved measurement of both length and width, and an identification of the plastic component using micro-Raman spectroscopy. The size of observed particles ranged from 75 μm to 161 μm at their largest cross-section (see Table 2). Additionally, some scanning electron microscopy images were made of three microplastics, to get a better idea of the surface morphology of these particles (see Fig. 2). All five particles had distinct colouring (see Fig. 1). The presence of these pigments in the particles interfered with the measurements of the plastic type, and as a result the spectra obtained were these for the pigments, not those for the plastic type (see Fig. 3). Three different pigments were measured: copper phthalocyanine (blue pigment), polychloro copper phthalocyanine (green pigment) and permanent red (red pigment). These are organic pigments with a non-natural origin, indicating the presence of anthropogenic particles in these samples. Additionally, these pigments are most commonly used in the plastics industry (Lewis, 2004), which strengthens the assumption that these particles are microplastics.

Plastics are relatively new materials, and as have only been produced for the past 60 years. Despite their young age, plastics have already invaded most marine habitats, and even the most pristine of environments, the Arctic deep sea is not been spared, as Bergmann and Klages (2012) recently demonstrated. The sea floor is considered as a sink for much of the marine plastics (Goldberg, 1997), but the mechanisms by which these materials reach the deep sea floor, however, are still poorly understood (Gregory, 2009). For larger plastic debris, the heavy fouling of floating plastics is a possible mechanism, as it increases density so that they sink to the sea floor. Microplastics, on the other hand could reach the sea floor as marine snow. This marine snow is produced as a biologically enhanced aggregation of small particles (Alldredge and Silver, 1988). These microaggregates normally contain phytoplankton, organic debris and clay particles which adhere together through the action of extracellular polymeric material exuded by living or dead cells. Sinking rates of marine snow are estimated to range from 1 to 368 m d^{-1} (Alldredge and Silver, 1988). The depths of the deep-sea sampling locations in this study could thus have been reached within a couple of days or after several years. Through the incorporation of microplastics in these microaggregates, even low-density plastic particles (such as polyethylene and polypropylene) that normally float on the sea surface can be transported to the sea floor. As such, it is hard to make any prediction on the plastic type (i.e. low-density vs. high-density plastic) of the recovered microplastics. Since the extraction technique was based on flotation using a 1.6 g cm^{-3} solution, we can state that the deep-sea microplastics must a have a similar or lower density. Most commercially available plastics, however, meet this specification.

We were able to show, for the first time ever, that microplastics are present in the top sediment layer of the deep-sea floor. Up to now, however, no conclusive statements can be made on how these microscopic particles were transported from the surface to the bottom of the oceans. Yet, their presence indicates that microplastics have invaded the marine environment to an extent that they appear to be present throughout the world's oceans and seas, including abyssal depths.

Acknowledgements

We thank crew and principal scientists of the following scientific cruises: RRS Discovery 229, Merian MSM13/3, Polarstern ANT-XXVIII/3 and Pourquoi pas? ROV Victor 6000 WACS cruise. We also thank Professor Strijckmans and his scientific team for access to and help with the micro-Raman spectroscopy and Professor Cnudde and Wesley De Boever for making the SEM-images.

Lisbeth Van Cauwenberghe is the recipient of a Ph.D. grant of the Agency for Innovation by Science and Technology (IWT, Belgium).

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