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Running title: Tsunami microplastic dispersal

Abstract

Microplastics have become widely dispersed throughout the marine environment in and around Japan since the 1960s, which correspond to the onset of mass plastic production and use in this

country. Our study documents a possible abrupt microplastics depositional event in continental shelf and deep-sea environments triggered by a tsunami. The sediment layers contaminated by microplastics correspond with sedimentary horizons where ^{137}Cs signals were measured, indicating deposition after 1960s nuclear tests. The microplastics were observed in the 2011 Tohoku-Oki tsunami deposits. Tsunamis can thus contribute to the wide dispersal of microplastics from coastal to deep-sea areas, and these anthropogenic particles can be used to date very recent turbidite deposits.

Introduction

The large-scale production and use of plastics (Geyer et al., 2017) only dates back to ~1960 in Japan. Although the first synthetic plastics, such as bakelite, appeared in the early 20th century, widespread use of plastics did not occur until after World War II (Geyer et al., 2017). The ensuing rapid growth in plastics production was extraordinary, and surpassed most other manufactured materials (Geyer et al., 2017).

Microplastics (i.e., size < 5 mm; Arthur et al., 2008) have been observed in various types of sediment from all aquatic environments, including rivers, estuaries, lagoons, lakes, and coastal and deep seas (Castaeda et al., 2014; Thompson et al., 2004; Eriksen et al., 2014; Sruthy and Ramasamy, 2017; Wills et al., 2017; Vianello et al., 2013; Corcoran et al., 2015; Zobkov and Esiukova, 2017; Van Cauwenberghe et al., 2013; Woodall et al., 2014; Fischer et al., 2015). Due to their relative chemical stability, the amount of sedimentary microplastics will increase year by year, although some are physically fragmented and chemically and biologically decomposed by UV radiation, microorganic activity, and weathering. Persistent Organic Pollutants are adsorbed onto marine plastic particles and then deposited on the seafloor (Urbanek et al., 2018).

There are a variety of vectors for how microplastics are transported in marine waters and subsequently settle on the continental margin and in the abyssal ocean (Marin et al., 2017). Identified microplastics pathways include sewage systems, riverine inputs, storm water outflows, atmospheric fallout, and pollution from maritime activity (Marin et al., 2017). Tsunamis could also be a pathway that delivers microplastics into marine environments, and could potentially transport massive amounts of plastic in a relatively short time.

On 11 March 2011, the Mw 9.0 2011 Tohoku-Oki earthquake resulted in a devastating tsunami (Toyofuku et al., 2014). Along the northeast Japan coast, tsunami waves reached maximum run-ups of 40 m, and travelled kilometres inland (Fig. 1a; Tsuji et al., 2011). This tsunami washed away an estimated 5 million tons of debris (Ministry of the Environment, Japanese Agency, 2012).

Almost 100,000 pieces of debris reached the North American coast via the Pacific Ocean (Murray et al., 2018). During transport, this debris (e.g., soil residue and vegetation) was temporarily stored within surface-water gyres of the Pacific Ocean (Ebbesmeyer et al., 2007; Moore et al., 2001). Some of this debris might have sunk to the deep seafloor below the gyres, but most was deposited on the seabed along the coast of northeast Japan.

Arai et al. (2013) reported in detail on a tsunami-generated turbidity current that transported siliciclastic materials from coastal areas to the deep seafloor during the 2011 Tohoku-Oki tsunami. In addition, microplastics might have been transported rapidly to the deep sea along the northeast Japan coast, by surface currents and turbidity currents.

In this study, we document microplastics found in sediments collected from the continental shelf and upper margin of the Japan Trench. We show that the sediment layers contaminated by microplastics correspond to sedimentary horizons where ^{137}Cs signals were detected, indicating deposition after the 1960s nuclear tests. Furthermore, microplastics were observed in the deposits related to the 2011 tsunami. This implies that tsunamis can lead to the wide dispersal of microplastics from coastal areas to the deep-sea floor.

Global problem of microplastic pollution in seawater and sediments: A contemporary geohazard for all marine lives and humans

Plastic pollution is now ubiquitous throughout the marine environment. Eriksen et al. (2014) estimated that a minimum of 5.25 trillion particles weighing 268,940 tons exist worldwide, and Jambeck et al. (2015) reported that annual emissions of the plastic waste from land into the ocean in 2010 were estimated to range between 4.8 and 12.7 million metric tons. Some of the microplastics are floating in the sea surface, but according Lebreton et al (2019), 99% of the plastics from land are missing

These missing plastics might exist in deep-sea and/or on deep-sea beds. Woodall et al. (2014) showed that microplastics could sink into the water column and deposit on seabeds. Choy et al. (2019) reported that they could be also transported vertically through the water column by biological processes. Thus, the plastics in the oceans might have dispersed in the water columns and sediments.

The most important global problem of microplastics is the fact that they may containvarious toxic chemicals as PCBs, DDTs and so on (e.g. Wang et al., 2018) adsorbed on their surface or present in their matrix. Through a food chain in marine environments, they can be concentrated in marine organisms (e.g. Eriksen et al., 2014), and finally in humans. It is one of current significant marine

geohazards for all marine lives and humans. Thus, we need to futher investigate the distribution and sinks of macro and microplastics in the oceans, not only in the water column but also in the sediments..

Topography and tsunami deposits of the Japan Trench

The topography along the Japan Trench has been described in detail by Kawamura et al. (2012) and Nitta et al. (2018), and is briefly summarised below.

A Mw 9.0 earthquake occurred on 11 March 2011 off the Pacific coast of northeast Japan (hereafter the 2011 Tohoku-Oki earthquake). It generated a series of large tsunami waves with run-up heights of >40 m, and caused widespread inundation along the northeast coast of Japan (Fig. 1a; Tsuji et al., 2011).

Using seismic wave inversion analysis, Ide et al. (2011) revealed that ca. 20 m of slip occurred at the hypocentre at a depth of 24 km (Fig. 1a), which developed into 80 m of slip on the seafloor (Ito et al., 2011). Such a large amount of slip at this shallow depth would almost certainly produce a large tsunami (e.g., Maeda et al., 2011; Satake et al., 2013), but there are several scenarios that might explain the focal mechanism of such large shallow slip, including dynamic overshoot (Ide et al., 2011), wedge extension (Tsuji et al., 2013), and a submarine landslide (Kawamura et al., 2012, 2014; Strasser et al., 2013; Tappin et al., 2014).

The Pacific Plate is being subducted to the west beneath northeast Japan at a rate of 9 cm yr^{-1} (Seno et al., 1989; Fig. 1a). Some convex-upwards parts of the upper and lower slopes have a slope of >10°, particularly in the region from 39°10'N to 40°30'N along the Sanriku Escarpment (Fig. 1a). The upper slope includes many large, convex-upwards, horizontally arcuate topographic features, indicative of submarine sliding of Neogene forearc basin sediments and sedimentary rock masses with widths and lengths of several kilometres (Kawamura et al. 2012). Two large submarine canyons exist in the convex topography (i.e., the Hachinohe and Miyako submarine canyons), which may have focused the downward transport of sediments (Fig. 1a).

According to Kanamatsu et al. (2017), high-impact earthquakes such as the 2011 event have repeatedly occurred along the Japan Trench and are recorded in marine sediments. Co-event sedimentation related to the 2011 event was identified by Arai et al. (2013), and is also evidenced by the detection of ^{134}Cs on the surface sediment in Japan trench, which is originated in the Fukushima Dai-ichi Nuclear Power Plant accident (Oguri et al., 2013).. As such, similar and older earthquake-triggered tsunami deposits have been preserved in deep-sea basins along the Japan Trench (Ikehara et al., 2016; Kanamatsu et al., 2017).

Materials and methods

Samples were collected offshore of Shimokita (northeast Japan) in August 2011, five months after the 2011 Tohoku-Oki tsunami. The study area is situated ~300 km north of the epicentre of the 2011 Tohoku-Oki earthquake (Fig. 1a; Japan Meteorological Agency, 2011 [URL]). Sediment cores from nine stations at water depths from 55 to 1963 m were collected with a conventional multi-core sampler (Fig. 1b and c). The shelf stations were described by Toyofuku et al. (2014), and the slope sites were documented by Fontanier et al. (2014).

Station 1 (water depth 55 m) is characterised by fine to medium sands with a 4.5-cm-thick mixed layer (^{210}Pb profile) in which terrigenous particles (e.g., quartz, feldspar, and lithic fragments) and volcanic material (e.g., pumice and glass) range in grain size from fine to coarse sand (Fig. 2) (Toyofuku et al., 2014). The sedimentary record recovered from Station 2 (water depth 81 m) is topped by a 4-cm-thick, coarsening-up layer composed of very poorly sorted, very coarse sand, with large (0.5–2.0 cm) shelly fragments. Station 3 (water depth 105 m) is characterised by a 3-cm-thick uppermost layer of medium to coarse sand (Fig. 2). At Station 4 (water depth 211 m), located just beyond the shelf-break, the sediments are also fine to medium sand, although the total ^{210}Pb profile indicates a mixed layer in the uppermost 10 cm (Toyofuku et al., 2014). Sandy particles from the upper 5 cm of this mixed layer are coarser than the underlying sediments (Fig. 2). Based on these results, Toyofuku et al. (2014) concluded that the 2011 tsunamigenic deposits occur at sediment depths of 0–5 cm at Station 1, 0–4 cm at Station 2, 0–3.5 cm at Station 3, and 0–5.5 cm at Station 4 (Fig. 2).

The slope stations 6 to 10 are characterised by bioturbated, greenish black, clayey sediments that contain foraminifera, volcanic ash, and diatoms. These stations are characterised by fine sediments with no evidence of recent physical disturbance (Fontanier et al., 2014).

Our methodology involved the following: (1) dividing the whole cores into analysed and archived halves; (2) visual and smear slide descriptions of the cores following ODP technical procedures (Mazzullo and Graham, 1988); (3) photographing the fresh surface of the cores; and (4) successive sampling of the inner parts of the core samples using 7-cm^3-sized transparent plastic cubes, for measurements of physical properties.

Grain size determinations

The grain size distribution was determined with a Mastersizer laser diffraction grain size analyser. Approximately 0.1 g of wet sediment for each sample was disaggregated in boiling water in

a glass beaker and then left for 24 h. Each sample was further disaggregated by ultrasonic treatment for 30–60 s just before measurement.

The grain sizes are presented on the phi scale as follows:

$$\emptyset = -log_2 \frac{d}{d_0}$$

where d = grain size (mm) and d_0 = 1 mm, which makes phi dimensionless.

Radionuclide measurements

^{210}Pb is a natural radionuclide of the uranium decay series, and has a half-life of 22.3 yr. In sediments, ^{210}Pb is derived from two sources: the decay of ^{226}Ra within the mineral matrix (i.e., the supported fraction) and the adsorption of ^{210}Pb atoms onto the surface of particles, which are ultimately derived from the decay of ^{222}Rn in the water column or from atmospheric deposition (i.e., the unsupported fraction). Unsupported ^{210}Pb is also called excess ^{210}Pb or $^{210}Pb_{ex}$, and can be used to determine recent mass accumulation rates over a timescale of ca. 100 yr (Koide et al., 1972; Nittrouer et al., 1979).

^{137}Cs with a half-life of 30 yr is an artificial radionuclide dispersed into the natural environment, mainly by nuclear bomb tests after 1953. The maximum ^{137}Cs fallout was recorded in 1963, and it decreased after the cessation of atmospheric nuclear bomb tests. In the marine environment, ^{137}Cs was supplied by both atmospheric fallout and in sediments discharged by rivers (Smith and Ellis, 1982; Ritchie and McHenry, 1990). Given that ^{137}Cs is used as a chronological tracer, ^{137}Cs profiles in sediments are commonly used in conjunction with $^{210}Pb_{ex}$ profiles to determine sediment accumulation rates (e.g., Baskaran and Naidu, 1995; Kato et al., 2003).

Measurements of radionuclide activities were undertaken on sediments from Stations 2, 6, 8, and 10 following the procedures of Wenzhöfer et al. (2016). We used a GWL 120230 high-performance germanium well detector (ORTEC, USA) and an APV9002 multichannel gamma-ray spectrum analyser (Techno AP, Japan). The plastic vessels containing the sediment powders were hermetically sealed and stored for >2 months to allow radioactive equilibrium between ^{226}Ra and ^{222}Rn to be established before analysis. $^{210}Pb_{ex}$ activities were calculated by subtracting ^{214}Pb (351.9 keV) activities from total ^{210}Pb activities, assuming radioactive equilibrium is established between ^{226}Ra to the supported ^{210}Pb in the mineral matrix. ^{137}Cs activities (661.6 keV) were also measured. Standard materials used for the measurements were CANMET DL-1a for ^{210}Pb (1.40 Bq g^{-1}) and ^{214}Pb, and IAEA-375 for ^{137}Cs (5.28 Bq g^{-1} at December 31 1991) , respectively. Counting times ranged from

86,400 to 259,200 s, which resulted in >1000 net counts for both ^{210}Pb and ^{214}Pb peak spectra. The net counts were calculated by Gaussian curve fitting using with KaleidaGraph 4.5 software (Synergy Software, USA).

The ^{210}Pb activities of cores from Stations 1, 3, 4, 7, and 9 were measured by alpha spectrometry of granddaughter ^{210}Po at CEREGE, France. Immediately after the cruise, wet sediment samples were transported to France and dried in the laboratory. Samples were dissolved in a mixture of HCl, HNO_3, and HF in the presence of ^{209}Po as a yield tracer. Po was plated spontaneously from 1.5N HCl onto Ag disks. Uncertainties were calculated by standard propagation of 1σ counting errors of the samples and blanks.

Microplastics

A protocol to extract and detect microplastics from sediments was proposed by Hanvey et al. (2017). This protocol was followed in the present study to determine laboratory blanks, in order to identify contamination from the laboratory or clothing and to ensure the microplastic content is not being overestimated (Hanvey et al., 2017).

To avoid microplastic contamination from air during the extraction process, we simplified the methods to extract microplastics by using dense media. Dense media flotation was conducted using a 1.6 g/cm^3 sodium polytungstate (SPT) ($Na_6H_2W_{12}O_{40}$) solution. The floated particles were collected on filter paper and dried at 60°C for 24 h. These particles were placed in glass bins and then all the particles were observed on smear slides using a polarising microscope to identify microplastics. During sample preparation, we did not use plastic tools (e.g., vinyl bags, plastic pipettes, and plastic brash), to eliminate post-depositional contamination. Following Kanhai et al. (2019), potential contamination was evaluated using air microplastic contamination checks. A petri dish was exposed to air during sample processing for ~30 min. Only a few blue microplastic fibres were found in each dish.

We counted the microplastics from all the sediment samples under a microscope (Fig. 2). If the samples had been contaminated by air plastic, then each sample would contain the same number of contaminant particles, which would still allow the original relative amounts of the microplastics in these sediments to be evaluated.

Results

Phi values of <4 correspond to sand, 4 to 8 to silt, and >8 to clay (Fig. 2). The grain sizes at Stations 1–4 are mostly sand, whereas those at Stations 6–10 are predominantly silt (Fig. 2).

Under a polarising microscope, we observed mineral grains, planktonic tests, and other grains, including seaweed and microplastics. The microplastics in the sediment samples are characterised by slightly yellow, red, and blue colours under plane- and cross-polarised light, and do not exhibit irregular extinction (Fig. 3). The microplastics are mostly transparent homogeneous materials with a smooth surface, but some have rough surfaces with fine asperities, presumably due to weathering. Most of the microplastics are fibres that are several tens of microns long, and only two plastic fragments were observed (at Stations 2 and 3; Fig. 3).

The microplastic contents tend to decrease with increasing distance from the coast and water depth (Fig. 2). Abundant microplastics are observed in the tsunami-generated turbidite layers at Stations 1–3 (Fig. 2), but not at Station 4. At Stations 4 to 10, the microplastics tend to be concentrated in the surface layers (Fig. 2). The highest microplastic concentrations are mostly in the sand layers.

$^{210}Pb_{ex}$ activities measured in the sediments and their depth profiles are shown in Fig. 2. The activities of ^{137}Cs measured in the cores and the vertical profiles do not show any distinct peaks indicating nuclear testing fallout maxima recorded in 1963. The activities of $^{210}Pb_{ex}$ in the sediment cores except for St.7 and 8 showed constant in the shallower part, especially top to 5~10 cm depth. These profiles suggest that surface sediment mixing is enhanced for these sites.

Discussion and concluding remarks

Our results indicate that microplastics have become pervasive across the deep seafloor offshore of Hachinohe. We detected microplastics in all the sediment samples, and their abundances tend to increase towards the surface layers in all cores (Fig. 2). This reflects the original depositional profile of the microplastics.

There are few studies of microplastics in marine sediments that can be compared with our own data. In deep-sea beds at water depths of >1000 m in the Atlantic Ocean and Mediterranean Sea, Van Cauweberghe et al. (2013) reported the presence of a few plastics of ~100 µm size in 25 cm^3 surface sediment samples at several sites. On the Irish continental shelf, Martin et al. (2017) reported a maximum of nine microplastic particles in the 5 mm to 250 µm size fraction in 26 cm^3 samples of surface sediment. In contrast to these open oceans, >90 microplastic particles

were counted in sediments collected from the Derwent Estuary, Tasmania, Australia (Will et al., 2017), thought to have been transported by rivers flowing through cities in the region.

The microplastics identified in the present study were concentrated in sand layers at Stations 1–3, and reach a maximum concentration of 16 particles per 7 cm^3, similar to previous studies. The deposition of these sand layers was related to the 2011 tsunami (Toyofuku et al., 2014), which implies that the tsunami was as an efficient but short-lived process of particle transport.

Arai et al. (2013) proposed that a turbidity current induced by the 2011 tsunami propagated over the deep-sea bed at >3000 m water depth. Oguri et al. (2013) inferred recent rapid sedimentation after the 2011 event in the Japan Trench using a deep-sea camera system and radionuclide analyses. Such rapid sedimentation would mostly result from the post-seismic events after the 2011 earthquake–tsunami, but could also be due to the main shock. Thus, the 2011 tsunami and post-seismic events transported microplastics onto the deep seafloor in the Japan Trench region.

The microplastics may have originated from coastal areas of northeast Japan and/or the upper landward trench slopes. A significant disturbance of the seafloor in the Sanriku area due to the 2011 Tohoku-Oki earthquake might have generated sediment resuspension and slope failure off the Sanriku slope (Usami et al., 2017). Usami et al. (2017) proposed that turbidites on a landward slope in the Japan Trench resulted from the deposition of a resuspended turbidity current that started on an upper slope (shallower than several hundred metres). Thus, some of the microplastics could have been resuspended by the 2011 event and transported by turbidity currents.

These microplastics in deep-sea surface sediments could be further transported to the Northwest Pacific Ocean by strong bottom currents along the Japan, Kuril, and Aleutian trenches, which originate from the Antarctic Bottom Current (Owen et al., 2001). In fact, Ogawa et al. (1996) reported a mannequin head in a fissure on the abyssal plane of the Pacific Plate at ca. 6300 m water depth.

Similar older earthquake-triggered deposits of the 1454 AD Kyotoku and 869 AD Jogan events have been preserved in deep-sea basins along the Japan Trench (Ikehara et al., 2016). The 1960 Chile, 1933 Showa Sanriku, and 1896 Meiji Sanriku tsunami events also affected this area. ^{14}C ages are typically used to date deep-sea sediments. However, it is difficult to determine such ages below the carbonate compensation depth (CCD), because any foraminiferal tests for ^{14}C dating would have been dissolved. . Furthermore, even sufficient amount of these tests could be obtained, reservoir effect must be considered to convert into calendar age (Alves, et al., 2018). In deep-sea

sediments below the CCD, age determinations can only be made based on tephra layers, ^{210}Pb measurements, and paleomagnetism (Kanamatsu et al., 2017).

The detection of microplastics in tsunami event layers indicates that deposition is younger than the 1960s. As such, it should be possible to identify the 2011/1960 and 1933/1896 tsunami deposits from the presence or absence of microplastics (Fig. 4), respectively. Microplastic detection in sediments as a dating tool is only applicable to very young sediments, however, it could be a useful method of dating deep-sea samples below the CCD, although taking care is needed to eliminate bioturbation and other disturbance effects.

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Figure Captions

Figure 1. Bathymetric maps and section of the study area. **(a)** Detailed topography along the Japan Trench. The run-up heights of the 2011 tsunami are shown as black bars along the Tohoku coast (Tsuji et al., 2011), and by arrows where it was >10 m (Goto et al., 2012). A star indicates the epicentre of the 2011 Tohoku-Oki earthquake. A black square outlines the location of Fig. 1b. **(b)** Sampling sites off Hachinohe, Japan. Stations 1–10 are located on the shelf and along the Hachinohe Submarine Canyon. The grayscale shows the gradient (slope angle) of the study area. **(c)** Approximate bathymetric profile from the coast to the deep sea.

Figure 2. Characteristics of the core samples. From left to right: core lithofacies, photographs, X-ray CT images, magnetic susceptibility, void ratio/median diameter, microplastic count per 7 cm^3, and radionuclides (solid circles = excess ^{210}Pb; open circle = ^{137}Cs). The arrows mark the tsunamigenic deposits identified by Toyofuku et al. (2014).

Figure 3. Photomicrographs of microplastics in different sediment intervals. (A) 0–2.5 cm at Station 1 (54.9 m water depth); (B) 0–2.38 cm at Station 2 (81.3 m water depth); (C) 0–2.25 cm at Station 3 (105 m water depth); (D) 0–2.0 cm at Station 6 (497 m water depth); (E) 0–2.0 cm at Station 7 (747 m water depth); (F) 0–2.0 cm at Station 9 (1249 m water depth).

Figure 4. Conceptual model of microplastic deposition by past tsunami events along the Pacific coast of northeast Japan. The stippled green column represents a deep-sea sediment column. The yellow layers are tsunami event layers from the 1896 Meiji Sanriku, 1933 Showa Sanriku, 1960 Chile, and 2011 Tohoku-Oki tsunamis, and red fragments are microplastics in sediments deposited since the 1960s.