Distribution of the geochemical signature caused by the 2011 Tohoku-oki tsunami in Misawa harbor, northern Japan

Mike Frenken1,2 · Piero Bellanova1,2 · Yuichi Nishimura3 · Klaus Reichert2 · Jan Schwarzbauer1

Received: 13 October 2021 / Accepted: 4 May 2022 / Published online: 26 May 2022 © The Author(s) 2022

Abstract

The 2011 Tohoku-oki tsunami left a characteristic geochemical signature in the sediments of the Misawa harbor on the Aomori coastline (northern Japan), not only in vertical stratigraphy but also in lateral distribution. Suitable indicator compounds for the tsunami impact were used to identify and characterize the distribution of geochemical patterns within the harbor area. Specific compounds are illustrating the different emission sources and distribution during the 2011 tsunami. Petrogenic-derived markers, such as hopanes and polycyclic aromatic hydrocarbons, provide information about the tsunami-related destruction of facilities and technical material and the subsequent release of, for instance, oil and grease. Linear alkylbenzenes and diisopropynaphthalene are used to identify sewage-derived contaminants released by the tsunami. Old burden markers such as dichlorodiphenyltrichloroethane and its metabolites or polychlorinated biphenyl signal erosion and rearrangement of contaminants present in the sediments prior to the tsunami. Distribution of the analyzed pollutant groups indicate the tsunami-related release through various emission sources and their potential origin. While petrogenic-derived pollutants revealed a significant local spread with hotspot formation near the release, sewage-derived compounds were widely distributed and originated from a diffuse source not necessarily located in the harbor area. In contrast to freshly released contaminants, old burden markers are characterized by erosion of contaminated pre-tsunami sediment, the remobilization of pollutants and subsequent deposition of these sediment-bound contaminants in the tsunami layer. The correlation between all pollutant groups by their preferred accumulation reveals that source-specific compounds show different emission sources but reveal also a topographical control of the pollutant distribution by the 2011 tsunami.

Keywords 2011 Tohoku-oki tsunami · Emission source · Geochemical signature · Distribution of geochemical marker · Anthropogenic marker · Tsunami geochemistry
1 Introduction

Highly populated coastal areas located in earthquake risk zones experience an increased hazard of tsunamis (Depietri 2020). In particular, Japan has been severely affected by several tsunamis in recent centuries (Goto et al. 2015). Most notable is the 2011 Tohoku-oki tsunami triggered by the eponymous earthquake with a magnitude of 9.0 MW (Simons et al. 2011), which caused great destruction along the northeastern coast of Japan. Due to the ever-increasing vulnerability of coastal communities to tsunamis caused by the rising population and building development in coastal areas (Imamura et al. 2019), research and science on such events are taking on an increasingly important role. The destructive events of the 2004 Indian Ocean tsunami and the aforementioned 2011 Tohoku-oki tsunamis have shown the world the importance of understanding the processes behind these events and improving protective measures.

An important part of tsunami research has always been sedimentological studies to understand the erosion, transportation, and deposition of material, but also to determine the inundation effects. In the last decade, other analytical methods have received greater attention. Inorganic geochemistry, with the detection of major elements and water-soluble ions, has been successfully applied to distinguish tsunami sediments from background sedimentation (Chagué-Goff et al. 2017 and references therein). However, the preservation, persistence, solubility, and alteration of inorganic elements show that inorganic geochemistry has limitations. Recently, the tsunami analysis has been extended by organic geochemistry, which offers some advantages through long persistence and insolubility of analyzed compounds. Using natural organic compounds, tsunami layers have been successfully identified (Alpar et al. 2012; Mathes-Schmidt et al. 2013; Shinozaki et al. 2015). Bellanova et al. (2019, 2020) implemented the analysis of persistent anthropogenic compounds, demonstrating that tsunamis can be detected and characterized by their pollution signature. The studies show the importance of geochemical analyses for extending the methods used in tsunami identification for a further understanding of tsunami processes.

Based on the studies effectively conducted and the successful identification of suitable organic geochemical indicator compounds, the scientific questions remain: (I) if it is possible to trace potential sources of tsunami-related pollutants; (II) if the tsunami left a distinct distribution pattern of contaminants; (III) if the topography is decisive for the deposition of the pollutants; (IV) if the geochemical compounds originated from diffuse sources, local point-sources, or remobilization. Based on these research questions, the aim of the study is to understand the contaminant distribution of each several different groups (e.g., old burdens, sewage indicators, and petrogenic markers), to trace the accumulation at specific locations, and to characterize different emission sources with their transport pathways.

2 Study area

The study area is located in the Aomori Prefecture in northern Japan. At the study area of the Misawa harbor, the coastal area is characterized by a 100–200 m-wide coastal lowland with a dune ridge running parallel to the shoreline and a 10–20 m-high terrace scarp ca. 200–400 m inland (Nakamura et al. 2012; Koiwa et al. 2014; Tanigawa et al. 2016). The coastal lowland and the terrace scarp are covered by coastal control forest of black pines (Pinus thunbergii) between landward of the dunes (Nakamura et al. 2012).
The coastal control forest is incised by the Mikawame creek south of the harbor (Fig. 1), which discharge into the Pacific Ocean (Koiwa et al. 2014).

Fig. 1 Overview of the study area. A Location of the study area in Japan. B Location of the studied transects in Misawa harbor
Misawa harbor itself covers an area of approximately 0.35 km² and consists of mostly paved areas and roads and several harbor buildings (Fig. 1). Landward of the control forest is a residential area located along the main Route 338 (Fig. 1; Nakamura et al. 2012). Furthermore, two access roads run through the forest (northern road between T8 and T7; southern road between T3 and T2; Fig. 1), connecting the harbor with the main road. The coastal forest at the southern and northern ends of the study area of the harbor is less wide than in the central part (Fig. 1).

The sampled transects have different characteristics, mainly related to topography. Transect T1 is located south of the harbor area landward of the recreational Miss Veedol Beach (Fig. 1). While the beach is relatively flat, a man-made heap is located in the transition from the shoreline to the control forest. The transects T2–T9 show similar characteristics, because they are all located in the control forest behind the harbor. In the transition from the harbor area to the forest is a dune with a local depression (swale) landward of it, after which the topography continuously increases (Figs. 1, 2). T10 is located north of the harbor landward of a seawall. Behind the seawall, a dune complex is present and the adjacent to the control forest (Figs. 1, 2).

The 2011 Tohoku-oki tsunami triggered by the namesake earthquake with the epicenter approx. 320 km apart of the study area caused massive damage to Misawa harbor and the surrounding area (Nakamura et al. 2012). A total area of 6 km² was affected in Misawa and 169 buildings destroyed (National Institute for Land and Infrastructure Management 2011; International Research Institute of Disaster Science 2013). Nearly the entire harbor area was covered with sediments from the tsunami inundation (Hazarika et al. 2013), and local run-up heights of 5.8 m were measured (Nakamura et al. 2012). The complete infrastructure in the harbor was affected by the tsunami, harbor buildings were partly destroyed and flooded, the seawall in the south and oil tanks were severely demolished (Nakamura et al. 2012; Bellanova et al. 2021). Furthermore, materials and other equipment, such as floating docks, boats, cars, barrels, buoys, and fishing material (nets), were transported inland and vice versa (Misawa City Board of Education 2012; Nakamura et al. 2012; Nandasena et al. 2012; Hazarika et al. 2013 Carlton et al. 2018). Furthest inundation was reported in the lower topographical areas in the southern part of the harbor along the Mikawame creek, reaching the residential areas 550 m inland (Bellanova et al. 2021), whereas the coastal forest in the harbor area was flooded to a maximum of 200–500 m (Bellanova et al. 2021).

3 Material and methods

3.1 Sample material

A field study was conducted along the Misawa coastline in November 2018 at nine coastal perpendicular transects (Fig. 1). Transects are numbered in ascending order extending from south to north (Table 1, Fig. 1). The cores taken are abbreviated MIS for the field location of the Misawa harbor. In total, 28 sedimentary sediment profiles were obtained by using a handheld geoslicer (see Table 2 for sampling locations and depth), and individual samples were taken from the 2011 Tohoku-oki tsunami layers investigated by Bellanova et al. (2021). Of each transect, two to four intact sediment profiles were obtained, from which the 2011 Tohoku-oki tsunami layer was sampled. At some locations, the tsunami layer was subsampled, based on sedimentological features (e.g., multiple sub-layers and mud caps). For vertical comparison in the geochemical signature, the overlying and underlying
layers encompassing the 2011 tsunami deposits were also sampled. Samples collected were placed in pre-cleaned aluminum-coated containers to avoid contamination and stored at 4–7 °C to minimize microbial alterations.

### 3.2 Total organic carbon (TOC)

For the preparation of TOC measurements, the samples were dried, macro plant residues (e.g., leaves and needles) were removed, and the material was homogenized. Determination of the TOC was performed with 100 mg ground material using the Elementar LiquiTOC II (Elementar Analysensysteme GmbH, Germany). All samples were measured twice to minimize the error margin, resulting in a standard deviation of 0.1–1.5%
3.3 Extraction and fractionation of sedimentary sample material

All samples were extracted using a solid–liquid approach. Overhead shaking with 110 mL of acetone (twice, for 4 and 24 h, respectively) and 110 mL of n-hexane (24 h) in an Erlenmeyer flask dissolve the organic-geochemical components from the sediments as described by Bellanova et al. (2019). Extracts obtained were combined in a separatory funnel and reduced in volume via rotary evaporation (at 300 mbar). If n-hexane is surplus during evaporation, an aqueous phase is formed, which was separated. Extracts were concentrated to approx. 1 mL, dried over anhydrous granulated sodium sulfate (Na₂SO₄), and desulfurized by adding activated copper powder in ultrasonic agitation.

Via column chromatography on a micro-column with activated silica gel (2 g; 40 mm; 60 Å; J.T. Baker™), the previously obtained extracts were fractionated into six fractions using eluents based on different solvent mixtures of n-pentane, dichloromethane (DCM), and methanol (MeOH) (according to Schwarzbauer et al. 2000). Thereafter, each individual

| Transect | Sediment profiles | Coordinates | Distance from coast (m) | Elevation (masl) |
|----------|-------------------|-------------|------------------------|-----------------|
| T1       | MIS 23            | 40° 40.454' N 141° 26.024' E | 600            | 10              |
|          | MIS 22            | 40° 40.456' N 141° 25.996' E | 630            | 13              |
|          | MIS 25            | 40° 40.455' N 141° 25.976' E | 660            | 12              |
| T2       | MIS 27            | 40° 40.607' N 141° 25.987' E | 520            | 8               |
|          | MIS 28            | 40° 40.606' N 141° 25.973' E | 550            | 10              |
|          | MIS 29            | 40° 40.607' N 141° 25.953' E | 580            | 13              |
| T3       | MIS 37            | 40° 40.715' N 141° 25.962' E | 275            | 8               |
|          | MIS 38            | 40° 40.710' N 141° 25.943' E | 300            | 10              |
|          | MIS 39            | 40° 40.711' N 141° 25.916' E | 325            | 12              |
|          | MIS 40            | 40° 40.708' N 141° 25.906' E | 350            | 13              |
| T4       | MIS 31            | 40° 40.769' N 141° 25.936' E | 280            | 9               |
|          | MIS 32            | 40° 40.769' N 141° 25.924' E | 305            | 11              |
|          | MIS 33            | 40° 40.764' N 141° 25.909' E | 330            | 13              |
|          | MIS 34            | 40° 40.767' N 141° 25.886' E | 360            | 16              |
| T6       | MIS 4             | 40° 40.877' N 141° 25.905' E | 285            | 9               |
|          | MIS 9             | 40° 40.872' N 141° 25.881' E | 315            | 12              |
|          | MIS 10            | 40° 40.869' N 141° 25.866' E | 340            | 15              |
| T7       | MIS 5             | 40° 40.935' N 141° 25.880' E | 290            | 11              |
|          | MIS 12            | 40° 40.930' N 141° 25.876' E | 305            | 12              |
| T8       | MIS 6             | 40° 40.987' N 141° 25.877' E | 275            | 10              |
|          | MIS 15            | 40° 40.987' N 141° 25.854' E | 300            | 12              |
|          | MIS 16            | 40° 40.987' N 141° 25.836' E | 330.5          | 13.5            |
|          | MIS 17            | 40° 40.990' N 141° 25.822' E | 350            | 15              |
| T9       | MIS 41            | 40° 41.104' N 141° 25.845' E | 270            | 9               |
|          | MIS 42            | 40° 41.103' N 141° 25.832' E | 290            | 10              |
|          | MIS 43            | 40° 41.104' N 141° 25.804' E | 325            | 14              |
| T10      | MIS 18            | 40° 41.321' N 141° 25.815' E | 80             | 7               |
|          | MIS 19            | 40° 41.309' N 141° 25.785' E | 125            | 11              |
Table 2  Concentration and ratios of all detected compounds normalized to TOC

| Core  | Description            | Sample depth (cm) | Tsunami depth (cm) | TOC (%) | Concentrations in ng/gTOC | Petrogenic marker | Sewage-derived marker | Old burden parameter | Maturity index |
|-------|------------------------|-------------------|--------------------|---------|---------------------------|-------------------|----------------------|---------------------|---------------|
|       |                        |                   |                    |         | hopanes | PAHs | LABs | DIPNs | DDX | PCBs | 22S/(22S + 22R) C32 | 22S/(22S + 22R) C31 |
| T1    | MIS 23 Tsunami         | 4–5               | 3–8                | 1.25    | 3600  | 34,000 | 1900  | 40    | 560  | 300  | 0.60            | 0.58            |
| MIS 22 | Tsunami               | 4–7               | 4–9                | 0.99    | 330   | 150,000 | 2400  | 110   | 310  | 410  | 0.67            | 0.55            |
| MIS 25 | Tsunami               | 3–5               | 2–7                | 0.13    | 950   | 1,000,000 | 11,000 | 170   | 2300 | 7.4  | 0.94            | 0.58            |
| T2    | MIS 27 tsunami         | 2–5               | 2–7.5              | 0.60    | 2500  | 590,000 | 4400  | 74    | 990  | <LOQ | 0.96            | 0.54            |
| MIS 28 | Tsunami               | 4–5               | 3–6                | 1.50    | 1100  | 83,000  | 1500  | 63    | 3100 | 320  | 0.58            | 0.61            |
| MIS 29 | Tsunami               | 2–4               | 1.5–4              | 0.89    | 3900  | 84,000  | 1400  | 1.3   | 1100 | 1700 | 0.85            | 0.55            |
| T3    | MIS 37 Tsunami         | 5–8               | 5–8                | 1.02    | 35,000 | 2,500,000 | 6600  | 200   | 790  | 1100 | 0.61            | 0.58            |
| MIS 38 | Tsunami               | 4–6               | 4–6                | 1.50    | 16,000 | 650,000 | 2900  | 52    | 420  | 240  | 0.61            | 0.63            |
| MIS 39 | Tsunami               | 6–8.5             | 6–9                | 5.43    | 4000  | 370,000 | 850   | 43    | 430  | 93   | 0.82            | 0.60            |
| MIS 40 | Woody-organic tsunami | 2–4               | 2–4                | 19.3    | 3300  | 120,000 | 1800  | 27    | 77   | 4.1  | 0.99            | 0.77            |
| T4    | MIS 31 tsunami         | 4–6               | 3–10               | 0.78    | 6800  | 450,000 | 3800  | 320   | 1100 | 610  | 0.61            | 0.59            |
| MIS 32 | Tsunami               | 3–4.5             | 3–7                | 1.72    | 2400  | 170,000 | 1900  | 130   | 530  | 390  | 0.65            | 0.65            |
| MIS 33 | Tsunami               | 4–5               | 3–5                | 3.45    | 2900  | 150,000 | 4900  | 190   | 370  | 570  | 0.62            | 0.58            |
| MIS 34 | Tsunami               | 2.5–4             | 2.5–4              | 5.75    | 2700  | 76,000  | 1200  | <LOQ  | 450  | 0.0  | 0.94            | 0.46            |
| T6    | MIS 4 Tsunami          | 0.5–3             | 0.5–6              | 0.59    | 9700  | 73,000  | 2300  | 70    | 49   | 390  | 0.62            | 0.56            |
| MIS 9  | tsunami               | 3–4               | 3–8                | 1.18    | 340   | 23,000  | 2800  | 37    | 66   | 5.7  | 0.68            | 0.60            |
| MIS 10 | Tsunami               | 5–6               | 5–6                | 2.09    | 940   | 27,000  | 2700  | 120   | 360  | 60   | 0.68            | 0.64            |
| T7    | MIS 5 tsunami          | 2–4               | 2–8                | 0.43    | 1200  | 95,000  | 12,000 | 250   | 300  | 1300 | 0.77            | 0.63            |
| MIS 12 | tsunami               | 5–8               | 5–8                | 1.43    | 410   | 41,000  | 1200  | 1.4   | 190  | 0.8  | 0.57            | 0.58            |
Table 2 (continued)

| Core Description Sample | TOC (%), Concentrations in ng/g TOC | Maturity index | Petrogenic marker | Sewage-derived marker | Old burden parameter | hopanes PAHs LABs DIPNs DDX PCBs |
|-------------------------|-----------------------------------|----------------|------------------|----------------------|---------------------|-----------------------------|
| MIS 19 Tsunami          | 37.9, 890, 19,000, 200, 1.4, 58, 1.9 | 0.98, 0.67     |                  |                      |                     |                             |
| MIS 18 Tsunami          | 2.17, 600, 47,000, 2900, 48, 130, 130 | 0.63, 0.59     |                  |                      |                     |                             |
| MIS 17 Tsunami          | 1.80, 3600, 45,000, 4200, 160, 360 | 0.76, 0.65     |                  |                      |                     |                             |
| MIS 16 Tsunami          | 0.09, 8400, 500,000, 9600, 290 | 0.53, 0.52     |                  |                      |                     |                             |
| MIS 15 Tsunami          | 1.5–4, < LOQ, 620,000, 11,000, 810 | 0.64           |                  |                      |                     |                             |
| MIS 14 Tsunami          | 2–5, 1.80, 3600, 45,000, 4200, 160, 360 | 0.76, 0.65     |                  |                      |                     |                             |
| MIS 13 Tsunami          | 2–5, 0.09, 8400, 500,000, 9600, 290 | 0.53, 0.52     |                  |                      |                     |                             |
| MIS 12 Tsunami          | 0.3–6, 4.9, 1800, 31,000, 38, 350 | 0.75, 0.76     |                  |                      |                     |                             |
| MIS 11 Tsunami          | 1.5–4, < LOQ, 620,000, 11,000, 810 | 0.64           |                  |                      |                     |                             |
| MIS 10 Tsunami          | 2–5, 0.09, 8400, 500,000, 9600, 290 | 0.53, 0.52     |                  |                      |                     |                             |
| MIS 9 Tsunami           | 5–6, 4.9, 1800, 31,000, 38, 350 | 0.75, 0.76     |                  |                      |                     |                             |
| MIS 8 Tsunami           | 2–5, 0.09, 8400, 500,000, 9600, 290 | 0.53, 0.52     |                  |                      |                     |                             |
| MIS 7 Tsunami           | 2–5, 0.09, 8400, 500,000, 9600, 290 | 0.53, 0.52     |                  |                      |                     |                             |
| MIS 6 Tsunami           | 2–5, 0.09, 8400, 500,000, 9600, 290 | 0.53, 0.52     |                  |                      |                     |                             |

Note: DIPNs = Dibenz[a]pyrene, Indeno[1,2,3-cd]pyrene.
fraction was spiked with 50 μL of internal surrogate standard solution containing 5.8 ng/μL fluoroacetophenone, 6.28 ng/μL d_{10}-benzophenone, and 6.03 ng/μL d_{34}-hexadecane. Total volume of the fractions was reduced to analytical volume (20–200 μL) for the measurement.

3.4 Gas chromatography–mass-spectrometry analysis (GC–MS)

Gas chromatography–mass spectrometry (GC–MS) measurements were taken for a qualitative identification and quantitative determination of geochemical compounds.

The analyses were performed on a quadrupole GC–MS system (Thermo Finnigan Trace GC/MS, Thermo Finnigan LLC, USA) with helium as carrier gas and equipped with a 30 m × 0.25 mm i.d. × 0.25 μm film ZB-5 fused silica capillary column (Zebron capillary GC column, Chrompack). The GC–MS was operating in full scan mode ranging from 35 to 500 m/z in positive electron impact ionization mode (EI+) with 70 eV electron energy. Of each fraction a volume of 1 μl was injected into the GC–MS with a starting temperature of 60 °C (injector temperature 270 °C), a splitless time of 60 s and a hold for 3 min of the start temperature. Followed by a heating rate of 3 °C/min to 310 °C with a final isothermal time of 20 min.

Qualitative identification of the organic compounds was achieved via the comparison of published data (e.g., Schwarzbauer 2006 and references therein; Chen et al. 2016) and mass spectra and gas chromatographic retention with those of mass spectral libraries (NIST 2014 database National Institute of Standards and Technology – U.S. Department of Commerce, USA). Based on the integration of specific ion chromatograms using XCalibur™ software (Thermo Fisher Scientific Inc., USA) and external four-point calibrations, the quantification was implemented. Quantification of the identified compounds was performed using individual and unique m/z values of the compound group. The surrogate standard is conducted to correct inaccuracies in volume reduction, retention time and measurements (Dsikowitzky et al. 2004). All calculated results of the individual fraction of the samples were normalized to TOC (ng/g_{TOC}), which is the most appropriate normalization in terms of grain size effect and organic content.

3.5 Geographic information system model

The overview map and 3D topographic model of the coastal strip were prepared using Esri ArcMap 10.2 and a Digital Elevation Model provided by GSI Japan. A satellite photograph from Google Earth is used to illustrate the study area. Via Esri ArcScene, a 3D topographic model with a small exaggeration was presented.

4 Results and discussion

The distribution of contaminants in the tsunami deposits of Misawa can provide evidence of processes, destruction, and depositional environments during the 2011 Tohoku-oki tsunami. For this study, different compound groups, such as sewage-derived and petrogenic-derived markers as well as chlorinated old burdens (Table 2), were identified and quantified. Previous studies show the concentration of pollutants (e.g., PAHs) in the tsunami deposits of Misawa (Bellanova et al. 2021). The results compare the vertical distribution of pollutants within the sediments as well as the lateral distribution across the surveyed
area. A comparison of the vertical and spatial distribution can provide information about transport processes during the 2011 tsunami. Each of the analyzed compound group has individual emission sources, and individual compounds were transported differently by the tsunami; thus, the results of specific compounds are providing insights into distribution and mechanisms of the 2011 tsunami.

### 4.1 Sewage-derived markers

Emission sources of sewage- and technical-derived markers during tsunami inundation are primarily through destruction of residential areas, but also through a washout of flooded sewers and drainage channels (such as Mikawame Creek). Human activities cause pollutant releases, making channels a potential pathway for urban effluents, road run-off, and industrial run-off. Flooding during the 2011 tsunami released, remobilized, and distributed these compounds and then deposited them in the tsunami sediments. Destruction of infrastructure and large-scale inundation (e.g., from the Misawa River observed by Koiwa et al. 2014) were impacts of the 2011 Tohoku-oki tsunami at the Misawa coast (Misawa City Board of Education 2012; Nakamura et al. 2012; Nandasena et al. 2012; Hazarika et al. 2013; Tanigawa et al. 2016).

Linear alkylbenzene (thereinafter LABs) is a by-product of synthetic detergents and is released into the environment mainly through domestic sewage effluents (Takada and Ishiwatari 1990; Chalaux et al. 1995; Ricking et al. 2003), whereas di-iso-propylnaphthalenes (thereinafter DIPNs) is technical additives with a usage in coating agents, adhesives and as substitutes of polychlorinated biphenyls (Peterman and Delfino 1990). Another use of DIPNs is as a dye solvent in the production of carbonless paper (Peterman and Delfino 1990; Franke et al. 2007) and as by-products in food packaging material (Zhang et al. 2008).

In Misawa harbor, the LABs show significant accumulation in the tsunami layers in contrast to the background concentration (Figs. 3, 4). The concentration ranges from 200 to 12,000 ng/gTOC in the tsunami sediments (Table 2). A uniform distribution of these pollutants is evident with the highest concentrations in the northern part of the harbor (Fig. 3). Strongest enrichments of LABs are mainly in the cores closest to the shoreline, and the increase is convergent with the N74°W direction of the wave observed by Nakamura et al. (2012) (Fig. 1). DIPNs shows a similar uniform distribution pattern as the LABs, with a maximum concentration in the north of the harbor area. The concentration ranges from 1.4 to 1300 ng/gTOC and is mostly highest in the cores closest to the shoreline. The cores further inland show nearly the same concentration as the background sediments (Fig. 4). The southernmost core, located outside the harbor area, is a peculiarity for both compounds, where the concentration is increasing inland. Interestingly, the residential area in the hinterland was destroyed by the tsunami at this location and could be a potential source of contaminants (Fig. 3).

The sewage-derived compounds have been introduced from outside the coastal strip (such as leaching and flooding of nearby river, residential areas, or other potential sources) and to a lesser extent from the harbor area. The contaminants show general accumulation in tsunami layers. The concentrations of the contaminants are varying within the transects. Deliberation of pollutants occurred due to the tsunami and subsequent deposition of these at specific locations within the study area. The results show that sewage-derived contaminants are always accumulated in the tsunami layer. Further, are concentration maxima for the majority of the transects observed within deposits found in topographical depression.
Fig. 3  Spatial distribution of sewage-derived contaminants in tsunami deposits within the Misawa harbor sample area; A linear alkylbenzene distribution (LABs); B diisopropynaphthalene (DIPN) distribution

Fig. 4  Comparison of sewage-derived marker concentration of pre-tsunami soil, tsunami, and post-tsunami soil; A LABs; B DIPNs
(e.g., MIS 18, MIS 42, MIS 4, MIS 37). As these pollutants are particle-associated, a controlling factor of their distribution is the topography, which also controls the deposition of the pollutant’s hosting sedimentary material. Therefore, the pollution distribution can be characterized as mostly topographically controlled.

The tsunami-driven release of pollution can be documented within the tsunami layer, which cannot be explained by the rearrangement or remobilization of particulate material.

4.2 Petrogenic markers

The 2011 Tohoku-oki tsunami released petroleum, oil, grease, and varnish (lacquer) through the caused destruction of the coastline, especially the harbor area, leading to a petrogenic pollution of the tsunami sediments. The petrogenic-specific markers can be used to determine the distribution of pollution and locate its emission source. Hopanes and, to a lesser extent, polycyclic aromatic hydrocarbons (thereinafter PAHs) can be used to trace petrogenic contamination.

Hopanes are fossil organic material occurring in petroleum and crude oil as ubiquitous components and are highly resistant to biodegradation (Silva et al. 2013). Detected concentration of hopanes reaches up to 35,000 ng/gTOC. The maturity indices of hopanes, \(22S/(22S + 22R)\) \(C_{32}\) and \(22S/(22S + 22R)\) \(C_{31}\) (Huang et al. 2014; Peters et al. 2005), indicate a mature signature and thus fossil material as source of the components. The maturity signal of the crude oil does not change after reaching the equilibrium and consequently indicates petrogenic contamination in the tsunami sites (Peters et al. 2005). The distribution of hopanes at the field site illustrates a uniform dispersion, with a maximum accumulation in the coastal cores (Figs. 5, 6). The central area of the harbor (T3, T4 and T6) shows the strongest enrichments of all samples and is additionally exemplified by lower background concentrations (T3) (Fig. 6). This enrichment could be due to a specific source from the harbor facilities. In general, the cores more inland show hardly any enrichment.

PAHs are persistent pollutants that are also ubiquitously present in fossil material. However, PAHs can be introduced into the environment not only as petrogenic pollution, but also by combustion and atmospheric input as pyrogenic contamination (Stogiannidis and Laane 2015). Assignment to a potential source of PAHs is difficult by applying ratios because these indicate a mixed presence of both types. PAH ratios should be considered as semi-quantitative values because they can be applied without concerns mainly when a single dominant emission source is present (Huang et al. 2014). The analyzed field site in Misawa harbor shows several potential emission sources. Therefore, distinguishing their origin is rather difficult, whereas pyrogenic substances can rather be considered as ubiquitous background deposit with possible tsunami overprinting. PAH concentration in the tsunami samples ranges from 19,000 to 2,500,000 ng/gTOC (Table 2). Distribution of PAHs is characterized by an enrichment in the southern parts of the harbor and a lower concentration in the northern harbor areas (Fig. 5). The exception is the southernmost transect (T1) with a concentration increasing inland, most likely due to the destruction of the residential area. Similarly, to the hopanes, a strong and centered maximum of the accumulation occurs in transects T2, T3, and T4. The cores further inland show no deviation from the background signal (Fig. 6).

Petrogenic pollution in the tsunami deposits were most likely entrained as a fresh contribution of non-particulate-bound pollutants, rather than by a remobilization of prior pollution. Potentially poor dispersion of petroleum, oil and grease, released by the observed harbor destruction, tipped oil tanks, transported barrels, and demolished...
Fig. 5  Spatial distribution of petrogenic-derived contaminants in tsunami deposits within the Misawa harbor sample area: A hopane distribution; B polycyclic aromatic hydrocarbon (PAH) distribution.

Fig. 6  Comparison of petrogenic-derived marker concentration of pre-tsunami soil, tsunami, and post-tsunami soil; A hopanes; B PAHs.
ships could be responsible for the multitude of emission sources releasing the petro-
genic pollutants (Misawa City Board of Education 2012; Nakamura et al. 2012; Nan-
dasena et al. 2012; Hazarika et al. 2013; Tanigawa et al. 2016; Bellanova et al. 2021). Contaminants reveal minimal distribution in the study area with high accumulation rates near the source. The deposition of petrogenic pollutants occurred in local depres-
sions, such as the small swale at the beginning of the control forest. Therefore, petro-
genic pollutants were released from several point sources in the harbor and deposited in the immediate vicinity as local pollutant hot spots.

4.3 Old burdens

During a tsunami wash-over, not only new pollutants are released into the environ-
ment, but already contaminated sediments are remobilized, transported and relocated (Bellanova et al. 2020). In predominantly industrial and agricultural areas, the pol-
lutants can be remobilized by soil erosion and redeposited in the tsunami sediments following the tsunami inundation. The process has been described by Bellanova et al. (2020) for the 2011 Tohoku-oki tsunami affecting the Sendai Plain.

Dichlorodiphenyltrichloroethane (DDT) with associated metabolites (DDD and DDE; collectively DDX) and polychlorinated biphenyls (PCB) with congeners penta-, hexa- and heptachlorobiphenyl were among the identified chlorinated compounds in the tsunami layers. Both compound groups are classified as persistent organic pollut-
ants (POPs) and are old burdens, which are forbidden since decades in most of the world (Scheringer 1999; Kucher et al. 2018). DDT was used as agricultural pesticide and in anti-fouling agents (Wu et al. 2016), while PCBs were mainly used as plasticiz-
ers in paints, coolants, and hydraulic fluids (Lang 1992).

The concentration of DDX is in the range of 49–3100 ng/g_{TOC} and thins out from the south to the north, except of T10 with higher concentrations (Table 2; Fig. 7). Mostly, the core closest to the coast indicates the highest values. The distribution varies along the entire coastline, for instance does the concentration increase in transect T1 inland. In contrast, PCBs have a uniform distribution in the study area with concentra-
tions up to 1700 ng/g_{TOC} (Table 2). However, unlike DDX, the concentration does not decrease in the north, but behaves similarly as in the south of the harbor. Comparable to DDX, the cores near the coast are the most enriched ones (Fig. 7).

Old burdens are not in general increased in tsunami deposits, but are also present as prior pollution in the underlying soil (Fig. 8). The geochemical pattern is differ-
ent from those of the fresh pollutant emissions. Therefore, the accumulation of old burdens has a different origin relative to the previously discussed pollutants released by the tsunami. This is related to their prior distribution in the environment as old bur-
dens. The inundating tsunami waves remobilized the sediment-bound old burdens from sedimentary sources, transported and re-deposited them. Particularly, in transects T3 and T8, many old burdens existed in the soils, which underwent a remobilization and rearrangement by the tsunami run-off to the nearshore areas of the transects. Like the deposition of newly released contaminants, the redistribution of old burdens is topo-
graphically controlled (see 4.1 Sewage-derived markers). Thus, the existing contami-
nation in the soils, which is redistributed by the force of the tsunami, is accumulated in the tsunami deposits.
Fig. 7 Spatial distribution of old burden contaminants in tsunami deposits within the Misawa harbor sample area; A DDX-metabolites distribution; B polychlorinated biphenyl distribution (PCBs)

Fig. 8 Comparison of old burden marker concentration of pre-tsunami soil, tsunami, and post-tsunami soil; A DDX-metabolites; B PCBs
4.4 Distribution and emission source of contaminants during tsunami impact

The 2011 Tohoku-oki tsunami impact caused a strong superposition of the normal background contamination levels at the coastline in Misawa and changed the geochemical signature. The distribution, accumulation, emission sources and pathways of the contaminants can be identified by correlating the vertical pollutant stratigraphy to their spatial distribution in the tsunami layers across the field site.

The vertical perspective indicates significant accumulations of organic pollutant compounds in the tsunami layer samples from Misawa compared to the surrounding layers (Figs. 4, 6, 8). This supports the observation by Bellanova et al. (2021) describing enrichments of PAHs and n-alkanes in the tsunami sediments of the Misawa harbor. Old burdens, however, show that certain substances are enriched in both the tsunami layers and in some underlying layers. Due to general higher concentrations of pollutants in the tsunami deposits, it can be concluded that the tsunami had an impact on the accumulation in the respective deposits.

Aside the vertical variation in the geochemical signature of tsunami deposits, the spatial accumulation in relation to the distribution of contaminants needs to be considered to draw conclusions about processes and mechanisms during the 2011 tsunami. At the first glance, the spatial distribution of all contaminants has similar patterns, with accumulation in the cores closest to the coast and a decreasing concentration inland. Similar accumulation from the coast to inland was described by Bellanova et al. (2021) for the transects T3 and T8 in the Misawa control forest.

When considering the sedimentological characteristics of tsunami deposits, especially the thickness (Table 2), a correlation of contaminant accumulation to sediment accumulation is obvious. Varying thickness in tsunami sediments is often related to topographic conditions in the inundated area (Abe et al. 2012; 2020), because larger amounts of sediments are often deposited in local depressions. At Misawa harbor, the accumulation of contaminants in tsunami deposits occurs also in a topographically controlled manner, as the highest concentrations of contaminants is evident at local depressions. These depressions are located in the transition between the harbor area and the control forest behind as small dune crest (Figs. 3, 5, 7), which is one of the topographically lowest points (~ 4–10 m above sea level; Fig. 2) in the control forest. Likewise, the thickest sandy tsunami deposits in the study area are identified at the same location behind the dune crest (e.g., MIS 18, MIS 37; Fig. 2; Bellanova et al. 2021). Most notably, stagnant water incorporated by the tsunami wash-over in local depressions, such as the swale behind the dune in the control forest, favors the increased accumulation of pollutants, especially over time. Another possibility is the ablation of substances from steeper to the topographically lowest locations and a subsequent accumulation. The backwash process, however, had only minor effects as it had less force for erosion and transport of material from the upper control forest area to the lower one (Bellanova et al. 2021). Importantly, another consideration is that the sources of contaminants are in the path of the wash-over (e.g., harbor facilities), not in the path of the backwash. Indicators of mainly inland transported tsunami wash-over deposits are the identified sedimentological features, such as fining upward sequences (Nakamura et al. 2012; Bellanova et al. 2021).

The transport of compounds and sediments is influenced by both inundation and to a lesser extent by the backwash of the tsunami, but the final deposition of pollutants and their hosting sediments are controlled by the topography of the study area. However,
other factors like the emission source and emission pathway play a decisive role in the initial distribution of organic pollutants.

Tracing the potential sources of tsunami sediment pollution is possible through the varying distribution and inference of emission pathways. A complete uniform distribution of contaminants could infer non-source-specific accumulation and the responsibility of accumulation by particle transport and sedimentation. Location-independent accumulation occurs as a result, indicating strong mixing of pollutants from diverse emission sources, such as the harbor, Mikawame creek, sewers, and road run-off. However, some contaminant groups do not have the same, uniform but different lateral distribution patterns, pointing to different but specific release processes or diverse properties of the compounds affecting the distribution during the tsunami. Local release of pollutants, in particular from the harbor facilities, has occurred (Nakamura et al. 2012; Bellanova et al. 2021).

The properties of the compounds are important because petrogenic materials, which tend to be nonpolar, lipophilic and hydrophobic, float with the inundated water only short distances before adhering to particulate material, whereas old burdens expect higher transport distances because they tend to be sediment-associated pollutants and are thus transported nearly as far as tsunami sediments.

Upon closer examination, three possibilities of transport mechanisms during the tsunami impact can be identified. First, a local contribution of newly released organic pollutants, from point sources in the harbor and residential area that are incorporated into the tsunami sediments. Due to the destruction during the tsunami, substances, such as oil and grease, were released but not transported far inland, as they show low dispersion potential based on their physicochemical properties. Their distribution is a punctiform contamination, in the transects T2, T3 and T4. Second, the contribution of new pollutants by an indeterminable, diffuse source was examined (Heim and Schwarzbauer 2013), which are not necessarily at the coastal strip of Misawa harbor. LABs and DIPNs were most likely released only in small quantities in the harbor and were therefore released from other locations (e.g., river washout) in the surrounding areas struck by the tsunami, transported by the tsunami wash-over and deposited in the control forest in Misawa. The sewage-derived markers illustrate a site-independent diffuse source deposited uniformly and topographically throughout the area. Old burdens represent the third distribution process, as they are remobilized and subsequently dispersed during the tsunami as sediment-associated pollution from the erosion of previously contaminated material.

Accumulation and distribution, of all these pollutants, thus depend on a complex combination of release and remobilization source, and on topographically controlled deposition within the study area. Due to the different distribution processes, the spatial geochemical signature of each indicative pollutant changes and different geochemical patterns can be identified for the tsunami layers.

The selected and discussed compounds are few preliminary examples, but are representatives by indicating high source-specificities. Thus, anthropogenic contaminants originating from different sources can be used to identify different distribution processes; however, their topographically controlled deposition needs to be considered.
5 Conclusions

Analyzing specific anthropogenic substances over a larger study area (Misawa harbor, northern Japan) with a high-resolution sampling density enabled to detect and interpret distribution patterns of contaminants transported by the tsunami. Additionally, various source-specific and tsunami-related organic markers allowed the characterization and classification of potential sources and the depositional conditions during the tsunami. The released anthropogenic pollution provides information about the destruction caused by the tsunami and its dispersion within the inundation area. Finally, the compounds provide evidence about possible remobilization by the 2011 tsunami erosion, transport, and redeposition.

Accumulation of contaminants in tsunami deposits of Misawa illustrates the impact and release of pollutants during the 2011 Tohoku-oki tsunami. Different emission pathways can be verified by the various sources of the pollutants. Petrogenic compounds were released as local emissions with an origin in the harbor area. During the tsunami, the petrogenic pollutants were transported only small distances and were deposited in a centered area behind the harbor facilities. Large-scale flooding of the harbor and surrounding areas is characterized by the release and input of sewage-derived pollutants. An exact determination of the source remains difficult, as it is a diffuse contribution of compounds (e.g., through destroyed sewers or the Mikawame creek). Not only newly released pollutant contribution but also remobilization of old contaminants occurred during the 2011 tsunami in Misawa. The contaminated sediments were relocated by the tsunami and accumulated its sediments. A deposition of all pollutants occurred in a topographically controlled manner, and the most dominant accumulation of pollutants has been detected in a swale landward of the dune separating the harbor from the control forest. As this case study is constrained in time and space through the application of anthropogenic pollutants targeting the pollution by the 2011 Tohoku-oki tsunami in a specific target area inland of the Misawa harbor. This specific approach can only be used for recent tsunamis (at least since industrial revolution) when anthropogenic pollutants were released in the environment. However, the approach of this case study can be used as a blue print for future studies. By the addition of other organic substances (especially natural compounds), historic or paleo-tsunamis can be targeted and insights into distribution processes and effects in time and space can be extracted from the geochemical signature of tsunami sediments.

Acknowledgements This study was financially supported by the German Research Foundation (DFG, SCHW750/22-1, RE1361/32-1). For her support during the fieldwork, we want to thank Olga Konechnaya. We would like to thank the head of the lab Yvonne Esser, for geochemical sample processing and analyzing parts of the sample set as well as Annette Schneiderwind for her technical support during GC-MS analysis.

Funding Open Access funding enabled and organized by Projekt DEAL. This study was granted by the German Research Foundation (DFG, RE1361/32-1, SCHW750/22-1)

Data availability All data that have contributed to the reported results are available from the corresponding author at request.

Code availability Not applicable.

Declarations

Conflict of 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.
References

Abe T, Goto K, Sugawara D (2012) Relationship between the maximum extent of tsunami sand and the inundation limit of the 2011 Tohoku-oki tsunami on the Sendai Plain, Japan. Sediment Geol 282:142–150. https://doi.org/10.1016/j.sedgeo.2012.05.004

Abe T, Goto K, Sugawara D (2020) Spatial distribution and sources of tsunami deposits in a narrow valley setting - insight from 2011 Tohoku-oki tsunami deposits in northeastern Japan. Prog Earth Planet Sci 7:1. https://doi.org/10.1186/s40645-019-0318-6

Alpar B, Ünlü S, Altunok Y, Özer N, Aksu A (2012) New approaches in assessment of tsunami deposits in Dalaman (SW Turkey). Nat Hazards 60(1):27–41. https://doi.org/10.1007/s11069-010-9692-5

Bellanova P, Frenken M, Richmond B, Schwarzbauer J, La Selle S-P, Griswold F, Jaffe B, Nelson A, Reicherter K (2019) Organic geochemical investigation of far-field tsunami deposits of the Kahana Valley, O‘ahu, Hawai‘i. Sedimentology 67(3):1230–1248. https://doi.org/10.1111/sed.12583

Bellanova P, Frenken M, Reicherter K, Jaffe B, Szczuciński W, Schwarzbauer J (2020) Anthropogenic pollutants and biomarkers for the identification of 2011 Tohoku-oki tsunami deposits (Japan). Mar Geol 422:106117. https://doi.org/10.1016/j.margeo.2020.106117

Bellanova P, Frenken M, Nishimura Y, Schwarzbauer J, Reicherter K (2021) Tracing woody-organic tsunami deposits of the 2011 Tohoku-oki event in Misawa (Japan). Sci Rep 11:8947. https://doi.org/10.1038/s41598-021-88199-3

Carlton JT, Chapman JW, Geller JB, Miller JA, Ruiz G, Carlton DA, McCuller MI, Treneman NC, Steves BP, Breitenstein RA, Lewis R, Bilderback D, Bilderback D, Haga T, Harris LH (2018) Ecological and biological studies of ocean rafting: Japanese tsunami marine debris in North America and the Hawaiian Islands. Aquat Invasion 13:1–9. https://doi.org/10.3391/ai.2018.13.1.01

Chagué-Goff C, Szczuciński W, Shinozaki T (2017) Applications of geochemistry in tsunami research: a review. Earth Sci Rev 165:203–244. https://doi.org/10.1016/j.earscirev.2016.12.003

Chalaux N, Takada H, Bayona JM (1995) Molecular markers in Tokyo Bay sediments: sources and distribution. Mar Environ Res 40:77–92. https://doi.org/10.1016/0141-1136(95)90001-8

Chen W-L, Xie Z, Wolschke H, Gandrass J, Kötke D, Winkelmann M, Ebinghaus R (2016) Quantitative determination of ultra-trace carbazoles in sediments in the coastal environment. Chemosphere 150:586–595. https://doi.org/10.1016/j.chemosphere.2016.02.051

Depietri Y (2020) The social–ecological dimension of vulnerability and risk to natural hazards. Sustain Sci 15:587–604. https://doi.org/10.1007/s11625-019-00710-y

Dsikowitzky L, Schwarzbauer J, Kronimus A, Littke R (2004) The anthropogenic contribution to the organic load of the Lippe river (Germany). part 2: quantification of specific organic contaminants. Chemosphere 57:1288–1293. https://doi.org/10.1016/j.chemosphere.2004.08.053

Franke S, Grunenberg J, Schwarzbauer J (2007) The isomer-specific analysis of di-iso-propynaphthalenes. Intern J Environ Anal Chem 87(6):437–448. https://doi.org/10.1080/03067310601025221

Goto T, Satake K, Sugai T, Ishibe T, Harada T, Murotani S (2015) Historical tsunami and storm deposits during the last five centuries on the Sanriku coast, Japan. Mar Geol 367:105–117. https://doi.org/10.1016/j.margeo.2015.05.009

Hazarika H, Kasama K, Suetsugu D, Kataoka S, Yasufuku N (2013) Damage to geotechnical structures in waterfront areas of northern Tohoku due to the March 11, 2011 tsunami disaster. Indian Geotech J 43(2):137–152. https://doi.org/10.1007/s40098-012-0021-7

Heim S, Schwarzbauer J (2013) Pollution history revealed by sedimentary records: a review. Environ Chem Lett 11:255–270. https://doi.org/10.1007/s10311-013-0409-3

Huang L, Chernyak SM, Batterman SA (2014) PAHs (polycyclic aromatic hydrocarbons), Nitro-PAHs, hopanes and steranes biomarkers in sediments of southern Lake Michigan, USA. Sci Total Environ 487:173–186. https://doi.org/10.1016/j.scitotenv.2014.03.131
Imamura F, Boret SP, Suppasri A, Muhari A (2019) Recent occurrences of serious tsunami damage and the future challenges of tsunami disaster risk reduction. Prog Disaster Sci 1:100009. https://doi.org/10.1016/j.pdisas.2019.100009

International research institute of disaster science (2013) HFA IRIDeS review preliminary report: focusing on 2011 great East Japan earthquake. International Research Institute of Disaster Science, Tohoku University Japan

Koiwa N, Kasai M, Kataoka S, Isono T (2014) Examination of relation with tsunami behavior reconstructed from on-site sequence photographs, topography, and sedimentary deposits from the 2011 Tohoku-oki tsunami on the Kamikitai Plain, Japan. Mar Geol 358:107–119. https://doi.org/10.1016/j.margeo.2014.08.009

Kucher S, Dskowitzy L., Ricking M, Sujatha CH, Schwarzbaumer J (2018) Degree of phenyl chlorination of DDT-related compounds as potential molecular indicator for industrial DDT emissions. J Hazard Mater 353:360–371. https://doi.org/10.1016/j.jhazmat.2018.03.062

Lang V (1992) Polychlorinated biphenyls in the environment. J Chromatogr A 595:1–43. https://doi.org/10.1016/0021-9673(92)85144-I

Mathes-Schmidt M, Schwarzbaumer J, Papanikolaou I, Syberberg F, Thiele A, Wittkopp F, Reicherter K (2013) Geochemical and micropaleontological investigations of tsunamigenic layers along the Thracian Coast (Northern Aegean Sea, Greece). Zeitschrift Für Geomorphol 57(4):5–27. https://doi.org/10.1127/0372-8854/2013/S-00153

Misawa city board of education (2012) Great East Japan earthquake memory of Misawa city. (in Japanese)

Nakamura Y, Nishimura Y, Putra PS (2012) Local variation of inundation, sedimentary characteristics, and mineral assemblages of the 2011 Tohoku-oki tsunami on the Misawa coast, Aomori, Japan. Sediment Geol 282:216–227. https://doi.org/10.1016/j.sedgeo.2012.06.003

Nandasena NAK, Sasaki Y, Tanaka N (2012) Modeling field observations of the 2011 Great East Japan tsunami: efficacy of artificial and natural structures on tsunami mitigation. Coast Eng 67:1–13. https://doi.org/10.1016/j.coastaleng.2012.03.009

Peters KE, Walters CC, Moldowan JM (2005) The biomarker guide: biomarkers and isotopes in petroleum systems and Earth, vol 2. Cambridge University Press, Cambridge, p 1132

Ricking M, Schwarzbaumer J, Franke S (2003) Molecular markers of anthropogenic activities in sediments of the havel and spree rivers (Germany). Wat Res 37:2607–2617

Scheringer M (1999) Persistenz und Reichweite von Umweltchemikalien. Wiley, p 203

Schwarzbauer J (2006) Organic contaminants in riverine and groundwater systems - aspects of the anthropogenic contribution. Springer, Heidelberg, p 465

Schwarzbauer J, Littke R, Weigelt V (2000) Identification of specific organic contaminants for estimating the contribution of the Elbe river to the pollution of the German Bight. Org Geochem 31(12):1713–1731. https://doi.org/10.1016/S0146-6380(00)00076-0

Shinozaki T, Fujiwara M, Ikehara M, Sawai Y, Tamura T, Goto K, Sugawara D, Abe T (2015) Marine biomarkers deposited on coastal land by the 2011 Tohoku-oki tsunami. Nat Hazards 77(1):445–460. https://doi.org/10.1007/s11069-015-1598-9

Silva TR, Lopes SRP, Spörl G, Knooers BA, Azevedo DA (2013) Evaluation of anthropogenic inputs of hydrocarbons in sediment cores from a tropical Brazilian estuarine system. Microchem J 109:178–188. https://doi.org/10.1016/j.microc.2012.02.012

Simons M, Minson SE, Sladen A, Ortega F, Jiang J, Owen SE, Meng L, Ampuero J-P, Wei S, Chu R, Helmlinger DV, Kanamori H, Hetland E, Moore AW, Webb FH (2011) The 2011 magnitude 9.0 Tohoku-oki earthquake: mosaicking the megathrust from seconds to centuries. Science 332:1421–1425. https://doi.org/10.1126/science.1206731

Stogiannidis E, Laane R (2015) Source characterization of polycyclic aromatic hydrocarbons by using their molecular indices: an overview of possibilities. In: Whitacre DM (ed) Rev Environ Contam Toxicol, vol 234, pp 49–133

Takada H, Ishiwatari R (1990) Biodegradation experiments of linear alkylbenzenes (LABs): isomeric composition of C12 LABs as an indicator of the degree of LAB degradation in the aquatic environment. Environ Sci Technol 24:86–91. https://doi.org/10.1021/es00071a009
Tanigawa K, Sawai Y, Namegaya Y (2016) Diatom assemblages within tsunami deposit from the 2011 Tohoku-oki earthquake along the Misawa coast, Aomori prefecture, Northern Japan. Mar Geol 396:6–15. https://doi.org/10.1016/j.margeo.2016.11.016

Wu C-C, Bao L-J, Tao S, Zeng EY (2016) Significance of antifouling paint flakes to the distribution of dichlorodiphenyltrichloroethanes (DDTs) in estuarine sediment. Environ Pollut 210:253–260. https://doi.org/10.1016/j.envpol.2015.12.012

Zhang K, Noonan GO, Begley TH (2008) Determination of 2,6-diisopropynaphthalene (DIPN) and n-dibutylphthalate (DBP) in food and paper packaging materials from US marketplaces. Food Addit Contam 25(11):1416–1423. https://doi.org/10.1080/02652203082163380

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Mike Frenken1,2 · Piero Bellanova1,2 · Yuichi Nishimura3 · Klaus Reicherter2 · Jan Schwarzbauer1

1 Institute for Geology and Geochemistry of Petroleum and Coal, RWTH Aachen University, Lochnerstrasse 4-20, 52056 Aachen, Germany
2 Neotectonics and Natural Hazards Group, RWTH Aachen University, Lochnerstrasse 4-20, 52056 Aachen, Germany
3 Institute of Seismology and Volcanology, Hokkaido University, Kita-10, Nishi-8, Kita-ku, Sapporo 060-0810, Japan