

# Marine biomarkers deposited on coastal land by the 2011 Tohoku-oki tsunami

Tetsuya Shinozaki · Shigehiro Fujino · Minoru Ikehara ·  
Yuki Sawai · Toru Tamura · Kazuhisa Goto · Daisuke Sugawara ·  
Tomoya Abe

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**Abstract** To determine how and what kind of marine-sourced biomarkers are transported and deposited on land by tsunami, we collected and analyzed samples of the 2011 Tohoku-oki tsunami deposits and the underlying and overlying soil at Sendai and Odaka, in northeast Japan. Characteristic hydrocarbons, such as short-chain *n*-alkanes, pristane, and phytane, were detected only in soil layers 0–2 cm below the tsunami deposits at both sites. Dinosterol originated from dinoflagellates was detected in a mud layer overlying sand deposits in Odaka. Such characteristic biomarkers were not detected in soil layers deeper than 2 cm beneath the tsunami deposits at either site, and none was found in the surface soil layer overlying the tsunami deposit in Odaka. Therefore, it is probable that the biomarkers were transported and deposited by the tsunami. The sand layer was highly

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T. Shinozaki (✉)  
Graduate School of Life and Environmental Sciences, University of Tsukuba, Tennodai 1-1-1,  
Tsukuba 305-8572, Japan  
e-mail: shinozakit@geol.tsukuba.ac.jp

T. Shinozaki · Y. Sawai · T. Tamura  
Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology,  
Central 7, Higashi 1-1-1, Tsukuba 305-8567, Japan

S. Fujino  
Faculty of Life and Environmental Sciences, University of Tsukuba, Tennodai 1-1-1,  
Tsukuba 305-0006, Japan

M. Ikehara  
Center for Advanced Marine Core Research, Kochi University, Monobe 200, Nankoku 783-8502,  
Japan

K. Goto · D. Sugawara  
International Research Institute of Disaster Science (IRIDEs), Tohoku University, Aoba 468-1,  
Aramaki, Aoba-ku, Sendai 980-0845, Japan

T. Abe  
Graduate School of Environmental Studies, Nagoya University, Furo-cho, Chikusa-ku,  
Nagoya 464-8601, Japan

permeable and low in clay or organic matter to which biomarkers could bind. Any biomarkers deposited with the sand probably leached into the underlying soil or were found in sediments richer in clay and organic matter such as tsunamigenic mud. Sediment samples were collected more than 2 years after the tsunami, indicating that the marine-sourced biomarkers were preserved for at least 2 years in the soil. In addition, a comparative analysis of sediment samples collected earlier indicated that characteristic biomarkers did not remain in the sand layer 3 months after the tsunami. These findings show the potential of using biomarkers as proxies to identify marine-sourced deposits on coastal land.

**Keywords** 2011 Tohoku-oki tsunami · Biomarker · Hydrocarbon · Dinosterol · Northeast Japan · Tsunami deposits

## 1 Introduction

The tsunami caused by the Tohoku earthquake (Mw 9.0) struck coastal areas in Japan on March 11, 2011. After the tsunami, a number of research groups conducted urgent surveys using sedimentological (e.g., Goto et al. 2011, 2012a, b; Richmond et al. 2012; Szczuciński et al. 2012), micropaleontological (e.g., Pilarczyk et al. 2012; Tanaka et al. 2012), mineralogical (e.g., Jagodziński et al. 2012), geomorphological (e.g., Tappin et al. 2012; Tanaka et al. 2014), and geochemical (e.g., Chagué-Goff et al. 2012a, b; Yoshii et al. 2013) approaches. Among these, Goto et al. (2011) showed that sandy tsunami deposits >0.5 cm thick were distributed over only 62 % of the inundation distance in the Sendai Plain. They suggested that geochemical markers may be useful to detect the maximum tsunami inundation limit on the basis of their observation that water-leachable chlorides were highly concentrated in fine fractions of the 2011 tsunami deposits. Chagué-Goff et al. (2012a) identified sulfur and chlorine 4.85 km inland from the shoreline (at about the tsunami inundation limit), in the absence of any other sedimentological evidence. They also reported a landward decreasing trend in the concentrations of geochemical elements (e.g., potassium, calcium, and strontium), indicative of the marine incursion and associated minerals such as feldspars and clay minerals. Water-leachable chlorides were present in tsunami deposits and underlying soil 2, 5, and 7 months after the 2011 tsunami (Chagué-Goff et al. 2012b).

Here, we focus on the presence and absence of biomarkers—specifically, different signatures from inorganic chemicals—in the 2011 tsunami deposits and soil. Biomarkers are molecular fossils originating from living organisms. They play a role as tracers of the particular processes or sources of flora or fauna from which they were produced. For example, lower *n*-alkane homologs (notably C<sub>15</sub>, C<sub>17</sub>, and C<sub>19</sub> *n*-alkanes) tend to be predominant in many algae, whereas higher *n*-alkane homologs (such as C<sub>27</sub>, C<sub>29</sub>, and C<sub>31</sub>) tend to be predominant in the leaf waxes of higher plants (Peters et al. 2007b). In paleoceanography, for example, biomarkers have often been used to estimate the variability of terrigenous organic carbon input by rivers into the ocean (e.g., Yamamoto and Polyak 2009) on the basis of variations in the concentrations of long-chain (C<sub>27</sub>, C<sub>29</sub>, and C<sub>31</sub>) *n*-alkanes. In that case, terrigenous inputs were identified by using biomarkers in oceanic sediments; in this coastal lowland area, however, we propose the opposite—an attempt to detect a marine event from terrestrial sediments by using biomarkers. Here, we examined how and what kind of marine-sourced biomarkers were transported to, and deposited on, coastal land by the 2011 tsunami in Japan.

## 2 Previous studies of biomarkers in tsunami geology

The use of biomarkers as indicators of marine incursions is still limited in tsunami geology. Alpar et al. (2012) attempted to identify historical tsunamis by using biomarkers at a coastal area in southwest Turkey. They measured normal and branched alkanes, fatty acids, and sterols in three sand layers and two mud layers. They reported that marine-sourced biomarkers were present in at least one of the sand layers and concluded that this sand layer was most likely a tsunami deposit. However, marine-sourced biomarkers were not detected in the other two sand layers. Ünlü et al. (2012) conducted a biomarker analysis of semi-dry lagoon sediments in southwest Turkey. They reported that it was difficult to identify possible tsunami deposits from biochemical data. However, the results indicate some influxes of marine water in a freshwater environment.

## 3 Study sites

### 3.1 Sendai

The Sendai plain is alluvial lowland characterized by beach ridges formed parallel to the coast, natural levees, and back marshes. It has experienced several tsunami disasters (Fig. 1), with evidence of them preserved as sandy tsunami deposits (Abe et al. 1990; Minoura and Nakaya 1991; Minoura et al. 2001; Sawai et al. 2008, 2012). The 2011 tsunami caused inundation to a distance of about 3.5–5.0 km inland in the study area (Geospatial Information Authority of Japan: <http://www.gsi.go.jp/kikaku/kikaku40014.html>) (Fig. 1c). The tsunami transported very coarse to medium sand that covered rice paddies as far as about 2.5 km inland (Abe et al. 2012; Goto et al. 2012a).

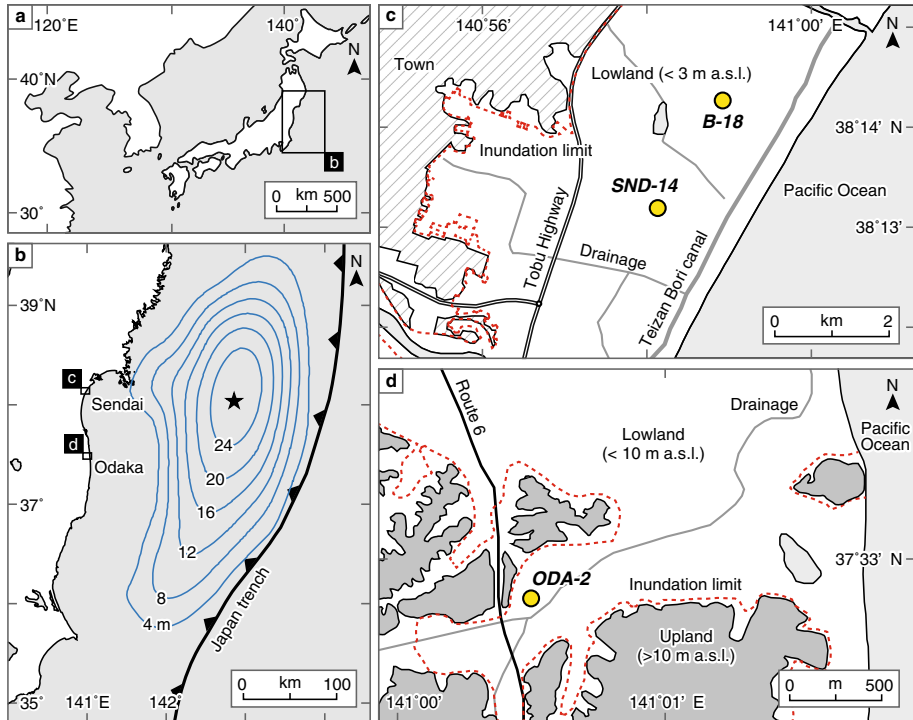
In March 2013, a 1.3-m-long sample (SND-14) was obtained by using a 2-m-long geoslicer (Nakata and Shimazaki 1997; Takada et al. 2002). The uppermost 12 cm was used for analysis. The sampling location was about 1.6 km inland from the shoreline and 0.2 m above sea level (Fig. 1c). Before the tsunami, this site had been used as a rice paddy field, but after the tsunami it was still uncultivated in March 2013, when we collected the sample.

In addition to the SND-14 samples, samples of sandy tsunami deposits and the overlying tsunamigenic mud layer were collected in June 2011 (Transect B-18 in Abe et al. 2012; Fig. 1c). These samples were also analyzed to examine whether the characteristics of the deposits had changed with time. This sediment sampling point was about 1.7 km inland from the shoreline and about 2.1 km northeast of SND-14 (Fig. 1c). The tsunamigenic mud layer was 1 cm thick, and the sand deposit was 5 cm thick.

### 3.2 Odaka

The Odaka site is located about 75 km south of Sendai (Fig. 1b). The lowland areas are surrounded by hills about 50 m high. This site has both historical and prehistoric tsunami deposits (Sawai et al. 2012). The 2011 tsunami caused inundation to a distance of about 2.6 km inland in the study area (Geospatial Information Authority of Japan: <http://www.gsi.go.jp/kikaku/kikaku40014.html>) (Fig. 1d).

A 1.5-m-long sample (ODA-2) was obtained in October 2013 by using a 2-m-long geoslicer, and the top 35 cm was used for analysis. The sampling location was about 1.8 km inland and 1.1 m above sea level (Fig. 1d). This site had been used for rice paddies



**Fig. 1** Location maps. **a** Japanese islands. **b** Eastern Honshu; the epicenter of the main shock of the 2011 magnitude-9 Tohoku-oki earthquake (black star) and the coseismic slip distribution (blue lines) is shown (Ozawa et al. 2011). **c** Sendai study area. The study area has extensive flat lowlands (<3 m a.s.l.). **d** Odaka study area. The yellow circles in (c) and (d) show the sampling sites. The red dashed lines in (c) and (d) show the inundation limits of the 2011 Tohoku-oki tsunami, as obtained from the Geospatial Information Authority of Japan (<http://www.gsi.go.jp/index.html>)

before the tsunami, but after the tsunami it was still uncultivated in October 2013, when we collected the sample.

## 4 Methods

### 4.1 Pretreatment and fundamental data

The subsamples were taken at 1.0-cm intervals. Part of each cut-up sample was frozen and kept at  $-20^{\circ}\text{C}$  for archival purposes, and the remainder was used for analysis. This sample was dried at  $60^{\circ}\text{C}$  for 2 days, and the water content (%) was calculated from the sample weights before and after drying. The dried sample was then homogenized with an agate mortar and pestle. About 1–2 g of a homogenized sample was weighed and ashed at  $550^{\circ}\text{C}$  for 4 h to estimate the loss on ignition (LOI, %), which is indicative of the organic content (Dean 1974). The remaining homogenized sample was split into two aliquots. One was used for the biomarker analysis (see Sect. 4.2), and the other was used for the analysis of total carbon (TC, %) and total nitrogen (TN, %). The split samples were weighed (about

4 mg in mud deposits and 20–100 mg in sandy deposits) in a tin cup, and measurements were performed with an Elemental Analyzer (Flash EA 1112, ThermFinnigan, Waltham, USA) at the Center for Advanced Marine Core Research (CMCR), Kochi University, Japan.

## 4.2 Biomarker analysis

Lipids were extracted from the homogenized sediment samples (about 2–3 g in mud deposits and 5–10 g in sandy deposits) to which 5 $\alpha$ -cholestane and cholesterol had been added as internal standards. For extraction, we used an Accelerated Solvent Extractor (ASE200 system, Dionex, Sunnyvale, USA) at 100 °C and 1,000 psi for 15 min with about 40 mL dichloromethane/methanol (95:5). The extract was saponified with 1.0 M KOH/methanol for 2 h at 70 °C. The neutral fraction was separated by extraction with hexane/dichloromethane (10:1); the acid fraction was then extracted with hexane after the remaining solution had been acidified to pH <1 by HCl. Column chromatography (Silica gel 60, Merck, Frankfurt, Germany; 0.040–0.063 mm) was then used to further separate the neutral fraction into four fractions: N1 (hydrocarbons), N2 (aromatic hydrocarbons), N3 (ketones), and N4 (alcohols and sterols). These fractions were separated with 2 mL hexane, 2 mL hexane/dichloromethane (2:1), 3 mL dichloromethane, and 4 mL dichloromethane/methanol (95:5), respectively. N4 fractions were converted to trimethylsilyl ether (TMS-ether) derivatives by using bis(trimethylsilyl)trifluoroacetamide (BSTFA) before analysis.

Gas chromatography with flame ionization detection (GC–FID: Agilent 6890 N Gas Chromatograph, Agilent Technologies, Santa Clara, USA) was used to analyze each hydrocarbon (N1), ketone (N3), and alcohol and sterol (N4). A Chrompack Capillary Column CP-Sil5CB column (60 m, 0.32 mm internal diameter, Agilent Technologies) was used. The oven temperature was increased from 50 to 120 °C at 30 °C/min, and from 120 to 310 °C (hold time: 35 min) at 6 °C/min. Each compound was identified by using GC–mass spectrometry (GC–MS: Agilent 5973 Network MSD, Agilent Technologies). All of the analyses were conducted at the CMCR.

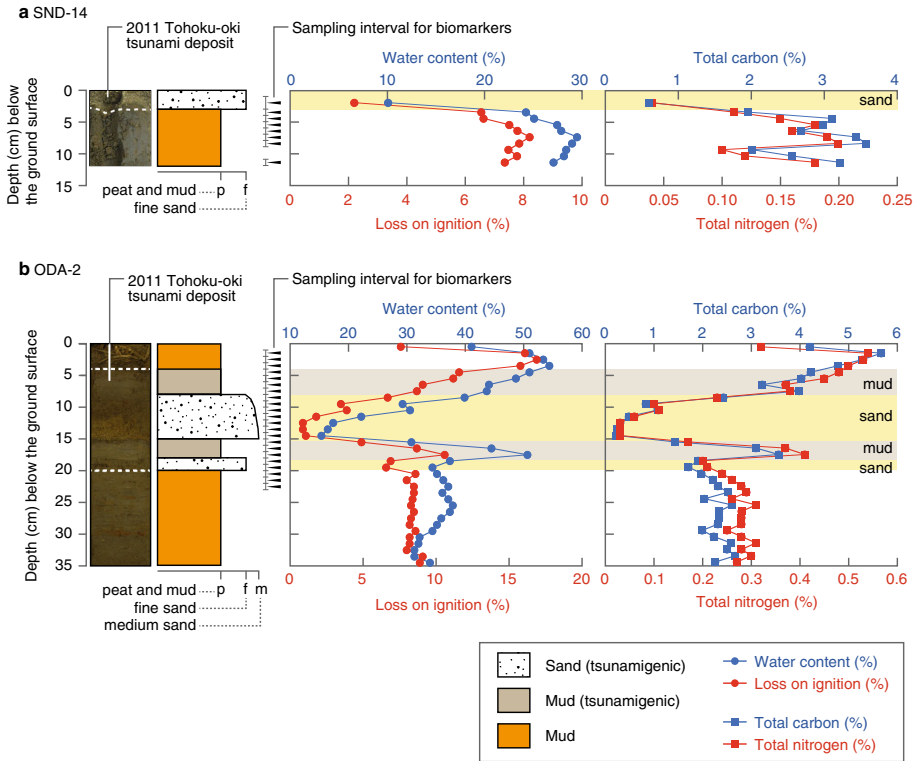
## 5 Results

### 5.1 Sendai

#### 5.1.1 Lithology

A 3-cm-thick fine sand deposit was observed at the top of the SND-14 sample (Fig. 2a). Rice paddy soil (organic-rich mud) was beneath the sandy deposits. An approximately 2-cm-thick mud overlay was observed 1 month after the tsunami in this area, but it could have been removed by erosion or anthropogenic factors by the time we collected the sediment samples 2 years later.

Water content, LOI, TC, and TN were lower in the sand and higher in the soil (Fig. 2a). TC and TN values were relatively low at a depth of 10–11 cm, as compared to those at the other soil depths (Fig. 2a).

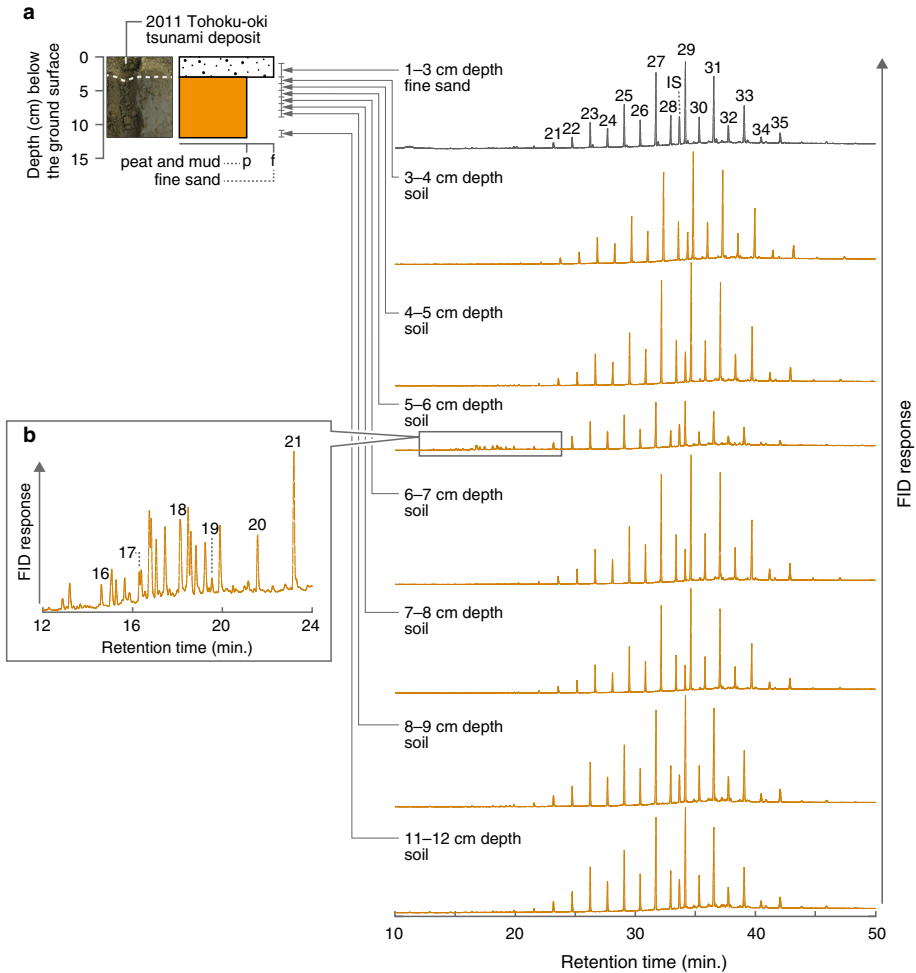


**Fig. 2** Sediment sample photographs and lithology, depth profile of water content (%), loss on ignition (%), total carbon (%), and total nitrogen (%) in the **a** SND-14 and **b** ODA-2 samples. *Black arrowheads* indicate sampling intervals for biomarkers

### 5.1.2 Biomarkers

Biomarkers were measured in one layer in the sand (1–3 cm depth) and seven layers in the soil (3–4, 4–5, 5–6, 6–7, 7–8, 8–9, and 11–12 cm depth) from sample SND-14 (Fig. 2a). *N*-alkanes occur as major components of the N1 fraction (hydrocarbons). They had a distribution with a maximum at  $C_{29}$  and other larger peaks at the odd-numbered *n*-alkanes ( $C_{23}$ ,  $C_{25}$ ,  $C_{27}$ ,  $C_{31}$ , and  $C_{33}$ ), whereas lesser peaks occurred at the even-numbered *n*-alkanes ( $C_{24}$ ,  $C_{26}$ ,  $C_{28}$ ,  $C_{30}$ , and  $C_{32}$ ) in every layer (Fig. 3a). Short-chain *n*-alkanes ( $C_{16}$ ,  $C_{17}$ ,  $C_{18}$ , and  $C_{19}$ ) were observed only at a depth of 5–6 cm (Fig. 3b). Alkenones (see Sect. 6.1), which occur as a component of the N3 fraction (ketones), were not detected in any layer, including at a depth of 5–6 cm. Sterols were observed as a component of the N4 fraction. Cholesterol and phytosterols, such as stigmaterol and  $\beta$ -sitosterol, were detected in every layer.

Figure 4 shows the hydrocarbon distribution of B-18 samples collected 3 months after the tsunami. Mud layer samples contained short-chain *n*-alkanes and pristane (Fig. 4a), whereas there were no characteristic hydrocarbons such as short-chain *n*-alkanes in the sandy deposits (Fig. 4b).

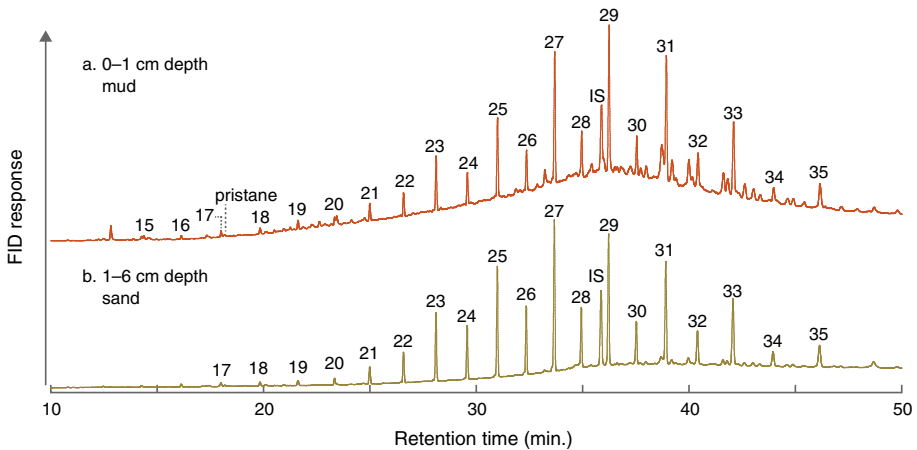


**Fig. 3** Gas chromatographs of hydrocarbons (N1 fraction) obtained from sample SND-14. **a** Results for the layer at 1–12 cm depth. *Gray* and *orange lines* show the results for sand and soil, respectively. Numbers indicate carbon numbers, and IS represents the 5 $\alpha$ -cholestane internal standards. **b** Expanded detail of the layer at 5–6 cm depth. Flame ionization detector (FID) response is a measure of the intensity of the signal, and retention time is the elapsed time at which the compound was detected

## 5.2 Odaka

### 5.2.1 Lithology

Sandy units were observed at depths of 8–15 and 18–20 cm (Fig. 2b). A 4-cm-thick mud layer (4–8 cm depth) covered the upper sandy deposits. An organic-rich mud deposit was intercalated between the two sand units at a depth of 15–18 cm. The sand and mud between 4 and 20 cm in depth must have been deposited by the 2011 tsunami, because sand would not naturally have been present at this location. The uppermost 4 cm of soil appeared to have accumulated naturally after the tsunami.



**Fig. 4** Gas chromatograms of the hydrocarbon fraction obtained from samples at transect B-18: **a** mud and **b** sand. The numbers indicate carbon numbers, and IS represents the  $5\alpha$ -cholestane internal standards

Water content, LOI, TC, and TN were lower in the sand; they were higher in the mud, especially at depths of 4–8 and 15–18 cm (Fig. 2b). The water content in the soil beneath the tsunami deposits was 31.3–37.9 %; the LOI was 8.0–9.1 %, the TC 1.98–2.67 %, and the TN 0.24–0.31 %.

### 5.2.2 Biomarkers

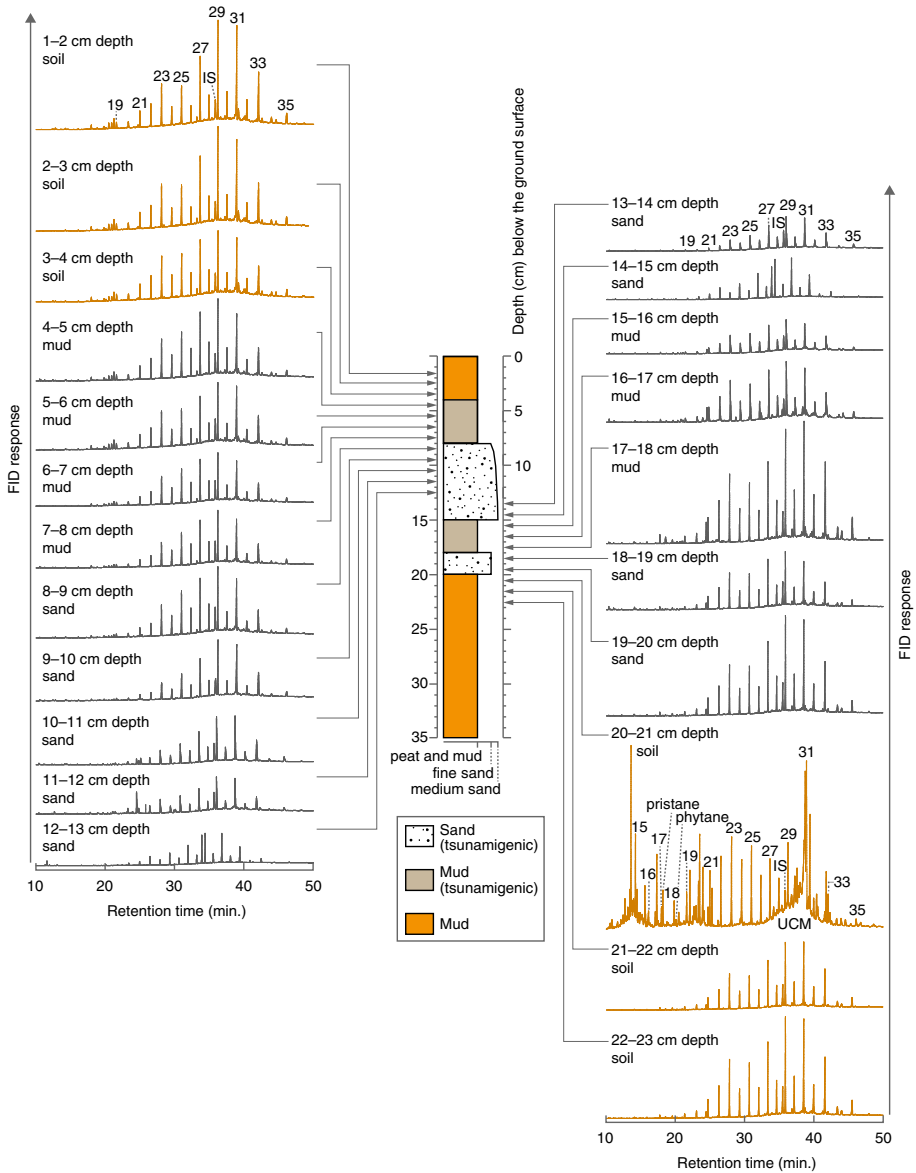
Biomarkers were measured in three layers in the surface soil (1–2, 2–3, and 3–4 cm depth), 16 layers in the 2011 tsunami deposits (at 1-cm intervals from 4 to 20 cm depth), and three layers in the underlying soil (20–21, 21–22, and 22–23 cm depth) from sample ODA-2 (Fig. 2b). *N*-alkanes had a unimodal distribution with a maximum at  $C_{29}$ , with the exception of the layer at 20–21 cm (Fig. 5). There was a distinct distribution pattern in the 20- to 21-cm-depth layer in which short-chain *n*-alkanes ( $C_{15}$ ,  $C_{16}$ ,  $C_{17}$ ,  $C_{18}$ , and  $C_{19}$ ), pristane (2,6,10,14-tetramethylpentadecane,  $C_{19}H_{40}$ , MW268), and phytane (2,6,10,14-tetramethylhexadecane,  $C_{20}H_{42}$ , MW282) were detected with a high baseline. No alkenones were observed in any layers. Cholesterol, stigmasterol, and  $\beta$ -sitosterol were detected in every layer. Dinosterol was confirmed only in the 5- to 6-cm-depth mud layer (Figs. 6, 7).

## 6 Discussion

### 6.1 Identification of biomarkers

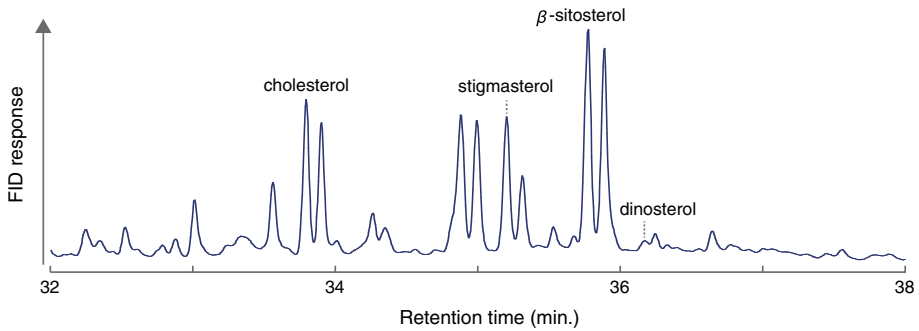
The distribution of hydrocarbons had a maximum at  $C_{29}$  with other larger peaks at the odd-numbered *n*-alkanes ( $C_{23}$ ,  $C_{25}$ ,  $C_{27}$ ,  $C_{31}$ , and  $C_{33}$ ), whereas lesser peaks occurred at the even-numbered *n*-alkanes ( $C_{24}$ ,  $C_{26}$ ,  $C_{28}$ ,  $C_{30}$ , and  $C_{32}$ ) in most of the layers measured at both Sendai and Odaka (Figs. 3a, 4, 5). This distribution pattern primarily indicates a contribution by higher plants (Eglinton and Hamilton 1963). In addition, short-chain *n*-alkanes, pristane, and phytane were detected in the soil layer at both sites (Figs. 3, 4, 5).  $C_{17}$  and  $C_{19}$  *n*-alkanes are predominant in algae (Gelpi et al. 1970), and  $C_{18}$  *n*-alkane is



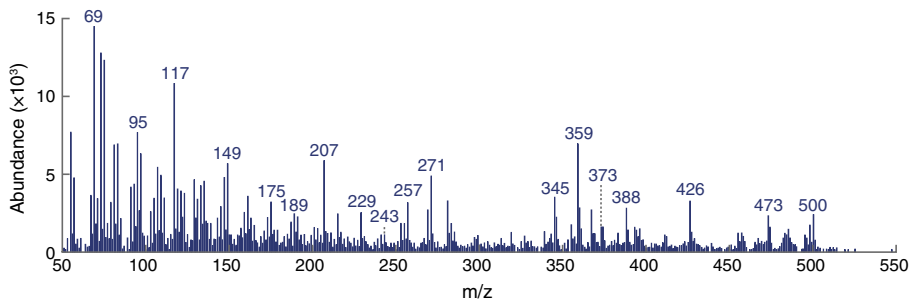


**Fig. 5** Gas chromatographs of hydrocarbons obtained from sample ODA-2. Gray and orange lines show the results of tsunami deposits and soil, respectively. Numbers indicate carbon numbers, and IS represents the 5 $\alpha$ -cholestane internal standards. UCM shows the existence of unresolved complex mixture

derived from fish (Mackie et al. 1974). Pristane is derived predominately from zooplankton (Blumer et al. 1963), benthos, and fish (Mackie et al. 1974). Phytane is derived predominately from zooplankton (Blumer and Thomas 1965) or sediment itself by biological activity (Ikan et al. 1975).



**Fig. 6** Gas chromatograph results of the N4 fraction from sample ODA-2 at the 5- to 6-cm-depth mud layer



**Fig. 7** Mass spectrum of dinosterol identified from sample ODA-2 at the 5- to 6-cm-depth mud layer. Numbers are  $m/z$  values (mass-to-charge ratios)

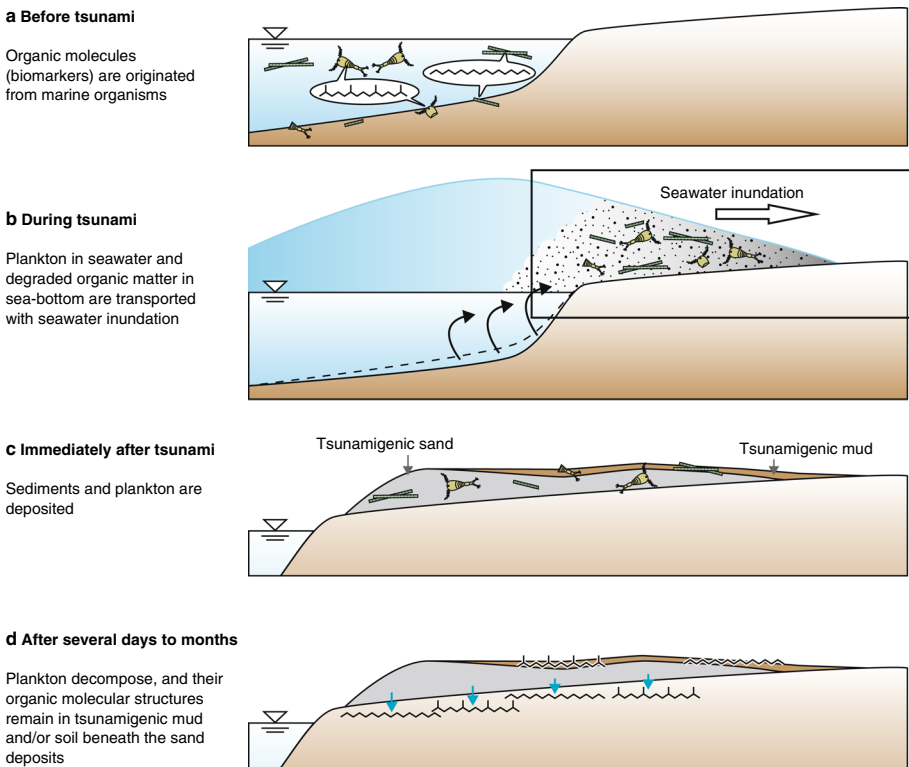
Long-chain  $C_{37}$ – $C_{39}$  unsaturated methyl and ethyl ketones, namely alkenones, are derived from several species of haptophytes, including the widely distributed coccolithophorids *Emiliania huxleyi* and *Gephyrocapsa oceanica* (Volkman et al. 1980; Marlowe et al. 1984; Conte et al. 1994). Alkenones were not detected in any measured layer at either site.

Cholesterol, stigmasterol, and  $\beta$ -sitosterol were detected in every measured layer. Animals tend to make cholesterol, whereas higher land plants typically produce stigmasterol and  $\beta$ -sitosterol (Peters et al. 2007a). Dinosterol originates from dinoflagellates (e.g., Boon et al. 1979) and is considered to be a good indicator as a marine biomarker. It was detected only in mud at a depth of 5–6 cm in Odaka.

## 6.2 Deposition of marine-sourced biomarkers

Characteristic hydrocarbons, such as short-chain  $n$ -alkanes, pristane, and phytane, were detected in the soil layer underlying the tsunami deposits in both the Sendai and Odaka sediment samples (Figs. 3, 5). The absence of these hydrocarbons in the deeper and surface soil layers strongly suggested that they were allochthonous. Additionally, dinosterol was detected in the mud layer (5–6 cm depth) at Odaka (Figs. 6, 7). Therefore, the measured short-chain  $n$ -alkanes, pristane, phytane, and dinosterol seemed to have been transported from the ocean by the 2011 tsunami.

The conceptual process of deposition of marine biomarkers is illustrated in Fig. 8: (1) Marine organisms, such as zoo- and phytoplankton, are composed of organic molecular structural materials. The partly degraded organic matter is deposited at the bottom of the sea. (2) Both marine organisms in seawater and degraded organic matter deposited in the sea bottom are transported to land during seawater inundation caused by a tsunami. (3) Sediment and plankton are deposited on land. (4) After several days to months, plankton decomposes by biodegradation or carbonate skeletons dissolve in the acidified soil, but their organic molecular structures remain in the soil as biomarkers. Marine-sourced biomarkers are concentrated in the mud layer overlying the sand or in the soil underlying sandy deposits, or in both. A similar process has been reported before for sea-derived elements (Chagué-Goff et al. 2012b, 2014). High concentrations of chloride, bromide, sulfate, and sodium were detected in the soil underlying the 20-cm-thick 2011 tsunami sandy deposits at least up to 1 year after tsunami inundation, and the concentrations decreased with depth. This result indicates that water-leachable ions (i.e., evidence of seawater) are mainly preserved not in the sandy deposits but in the soil beneath them. Marine-sourced biomarkers were also concentrated in the soil underlying sand deposits, therefore indicating that seawater evidence is not necessarily recorded in the sandy tsunami deposits themselves but in the underlying soil over time. The question arises then as to why no characteristic biomarkers were observed in the mud layer intercalated between the sand

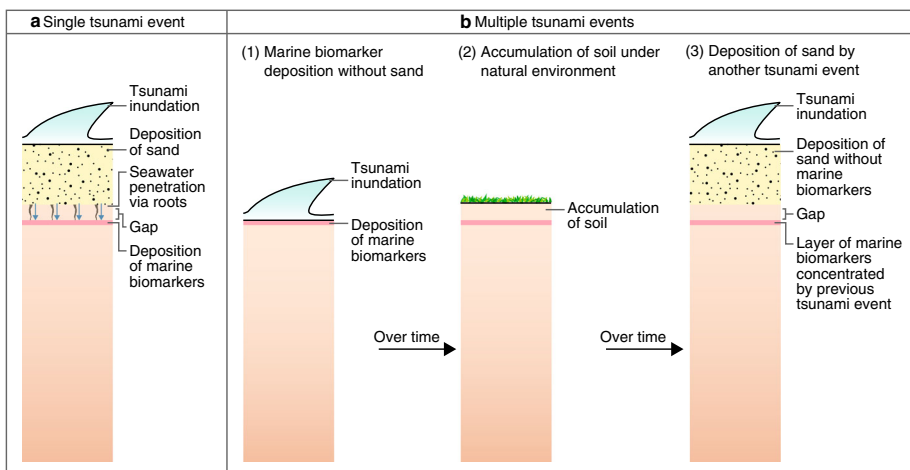


**Fig. 8** Marine biomarker deposition process: **a** before tsunami, **b** during tsunami, **c** immediately after tsunami, and **d** after several days to months

units in the ODA-2 sample? Unfortunately, we cannot answer this question from our existing data. One possibility is that the mud layer did not originate from the sea bottom but from another source. However, even freshwater mud transported by seawater could contain marine organisms. Another possibility is that marine-sourced biomarkers were diluted by terrestrial organic materials and therefore were not present in detectable amounts. Interestingly, dinosterol was detected only in the mud layer overlying sand at Odaka. This result indicates that the dinosterol concentration in the ocean is probably low. For the same reason, alkenones derived from specific coccoliths were absent, or at least not detected, in all layers analyzed at both sites.

In addition to the presence of marine-sourced biomarkers, another notable feature was observed only in the 20- to 21-cm-depth sample from Odaka. There was a broad and marked rise of the baseline (Fig. 5), probably as a result of contamination with unresolved complex mixture (UCM), most likely biodegraded and low-maturity oils (Meyers and Takeuchi 1981; Gough and Rowland 1990). Because there is no evidence for UCM in either terrigenous or marine organic matter, their presence in this layer indicates that they were transported by the tsunami in addition to the marine-sourced hydrocarbons. The UCM contamination might have originated from low-maturity oil deposited on the seafloor or oil spilled from broken vehicles and ships. Although there is no conclusive evidence of the source, an important point is that UCM is never derived from natural conditions. Its presence indicates that it was provided by some event—in this case, the tsunami.

The marine-sourced hydrocarbons were concentrated 2 cm below the tsunami deposits in SND-14 (Fig. 3), whereas they were detected immediately beneath the tsunami deposits in ODA-2 (Fig. 5). It is possible that seawater penetrated 2 cm into the soil layer via dense roots. Rice paddy soil contains plant materials, and the region was fallow in March when the tsunami occurred. However, there could be more than one possible interpretation in the case of paleotsunami deposits. If there is a slight gap between a sand layer and a layer containing marine-sourced biomarkers, we cannot necessarily differentiate whether they were formed by a single tsunami event or by multiple tsunami events. If there was a single tsunami event, the depositional process was likely as follows (Fig. 9a): Sand is deposited



**Fig. 9** Conceptual diagram of how a slight gap can be formed between a sand layer and a layer with concentrated marine biomarkers: **a** single event and **b** multiple events

on the surface by tsunami inundation, and marine biomarkers are then concentrated in the underlying soil by seawater penetration via roots. This case is similar to the case of the Sendai sample. If there were multiple tsunami events, the depositional process was likely as follows (Fig. 9b): (1) Marine-sourced biomarker deposition is caused by tsunami inundation without sand deposition. (2) Soil accumulates naturally over time. (3) Sand is deposited by another tsunami. The latter case is not likely, however, because there was no evidence of marine biomarkers in the second tsunami event, even though sand was transported by seawater flow. From this viewpoint, even if there is a slight gap between a sand layer and the layer containing marine-sourced biomarkers, it seems quite probable that these depositions were formed by a single tsunami event.

### 6.3 Preservation of marine-sourced biomarkers

Evidence of marine-sourced biomarkers was detected at Sendai 2 years after the tsunami and at Odaka 2.5 years after the tsunami. Although further research is necessary to reveal temporal changes in the biomarker concentrations, it is important to emphasize that the marine-sourced biomarkers were preserved for at least 2 years. Chagué-Goff et al. (2014) reported the time variations in the contents of soluble ions collected at Sendai 2, 5, and 11 months after the 2011 tsunami. Sulfate concentrations were even higher in February 2012 than they were in August 2011 in the soil at site WP 327. At this site, the tsunami deposit consisted of a sandy layer overlain by a mud cap and the underlying soil was predominantly silt. However, concentrations generally decreased with time, particularly where the tsunami deposits and underlying soil were sandy (sites WP325 and WP326 in the work of Chagué-Goff et al. 2014). This suggests that the concentration of water-leachable ions could generally decrease over time, most likely because it can easily be diluted by water flow such as precipitation and groundwater movement. In addition, in the 2004 Indian Ocean tsunami, salinity (represented by electrical conductivity,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , and  $\text{Cl}^-$ ) derived from the tsunami was almost eliminated after one rainy season (Szczeniński et al. 2007; Chandrasekharan et al. 2008; Kume et al. 2009; Raja et al. 2009; Nakaya et al. 2010). Nakaya et al. (2010) reported that soil salinity was almost completely eliminated by rainfall of 1,000 mm or more. More than 2,340 mm of precipitation was recorded between March 2011 and February 2013 in Sendai, and more than 3,400 mm was recorded between March 2011 and September 2013 in Haramachi (the closest meteorological weather station to Odaka, about 10 km away; Japan Meteorological Agency: <http://www.jma.go.jp/jma/index.html>). Even though both sites had a high level of precipitation, the marine-sourced biomarkers were still observed in high concentrations.

Marine-sourced biomarkers were not detected in the sand layer of the B-18 sample collected 3 months after the tsunami (Fig. 4). Although we cannot speculate on whether characteristic hydrocarbons had penetrated the underlying soil, because there were no soil samples available from the time shortly after the tsunami, the data suggest that detectable amounts of marine-sourced biomarkers were not preserved in the sand layer 3 months after the tsunami.

## 7 Conclusions

Here, we presented a profile of marine-sourced biomarkers transported by a tsunami. On the basis of our biomarker analyses of the 2011 Tohoku-oki tsunami deposits collected at Sendai and Odaka, we found that (1) tsunamigenic biomarkers, such as short-chain *n*-

alkanes, pristane, phytane, and dinosterol, were concentrated in the soil layer underlying the sandy tsunami deposits or in the tsunamigenic mud layer overlying the sand deposits, or in both; (2) the biomarkers were preserved for at least 2 years; and (3) the biomarkers seemed to move from the sand layer quickly—in this case, within 3 months following the tsunami. These findings show the potential of using biomarkers as proxies for identifying marine-originated deposits on coastal land. For further applications (e.g., research into paleotsunami), more case studies of modern tsunami and paleotsunami are needed.

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## References

- Abe H, Sugeno Y, Chigama A (1990) Estimation of the height of the Sanriku Jogan 11 earthquake-tsunami (AD 869) in the Sendai Plain. *J Seismol Soc Jpn (Zishin)* 43:513–525 (in Japanese with English abstract)
- 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. doi:10.1016/j.sedgeo.2012.05.004
- Alpar B, Ünlü S, Altınok Y, Özer N, Aksu A (2012) New approaches in assessment of tsunami deposits in Dalaman (SW Turkey). *Nat Hazards* 60(1):27–41. doi:10.1007/s11069-011-9951-0
- Blumer M, Thomas DW (1965) Phytadienes in zooplankton. *Science* 147:1148–1149. doi:10.1126/science.140.3570.974
- Blumer M, Mullin MM, Thomas DW (1963) Pristane in zooplankton. *Science* 140:974. doi:10.1126/science.147.3662.1148
- Boon JJ, Rijpstra WIC, Lange FD, Leeuw JWD, Yoshioka M, Shimizu Y (1979) Black Sea sterol—a molecular fossil for dinoflagellate blooms. *Nature* 277:125–127. doi:10.1038/277125a0
- Chagué-Goff C, Andrew A, Szczuciński W, Goff J, Nishimura Y (2012a) Geochemical signatures up to the maximum inundation of the 2011 Tohoku-oki tsunami—implications for the 869AD Jogan and other palaeotsunamis. *Sediment Geol* 282:65–77. doi:10.1016/j.sedgeo.2012.05.021
- Chagué-Goff C, Niedzielski P, Wong HKY, Szczuciński W, Sugawara D, Goff J (2012b) Environmental impact assessment of the 2011 Tohoku-oki tsunami on the Sendai Plain. *Sediment Geol* 282:175–187. doi:10.1016/j.sedgeo.2012.06.002
- Chagué-Goff C, Wong HKY, Sugawara D, Goff J, Nishimura Y, Beer J, Szczuciński W, Goto K (2014) Impact of tsunami inundation on soil salinisation: up to 1 year after the 2011 Tohoku-oki tsunami. In: Kontar YA, Santiago-Fandiño V, Takahashi T (eds) *Tsunami events and lessons learned: ecological and societal significance*. Springer, Berlin, pp 193–214
- Chandrasekharan H, Sarangi A, Nagarajan M, Singh VP, Rao DUM, Stalin P, Natarajan K, Chandrasekaran B, Anbazhagan S (2008) Variability of soil–water quality due to Tsunami-2004 in the coastal belt of Nagapattinam district, Tamilnadu. *J Environ Manag* 89:63–72. doi:10.1016/j.jenvman.2007.01.051
- Conte MH, Volkman JK, Eglinton G (1994) Lipid biomarkers of the haptophyta. In: Green JC, Leadbeater BSC (eds) *The haptophyte algae*. Clarendon Press, Oxford, pp 351–377
- Dean WJ (1974) Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. *J Sediment Petrol* 44(1):242–248. doi:10.1306/74D729D2-2B21-11D7-8648000102C1865D
- Eglinton G, Hamilton RJ (1963) The distributions of alkanes. In: Swan T (ed) *Chemical plant taxonomy*. Academic Press, California, pp 187–217
- Gelpi E, Schneider H, Mann J, Oro J (1970) Hydrocarbons of geochemical significance in microscopic algae. *Phytochemistry* 9:603–612
- Goto K, Chagué-Goff C, Fujino S, Goff J, Jaffe B, Nishimura Y, Richmond B, Sugawara D, Szczuciński W, Tappin DR, Witter RC, Yulianto E (2011) New insights of tsunami hazard from the 2011 Tohoku-oki event. *Mar Geol* 290(1–4):46–50. doi:10.1016/j.margeo.2011.10.004

- Goto K, Sugawara D, Abe T, Haraguchi T, Fujino S (2012a) Liquefaction as an important source of the AD 2011 Tohoku-oki tsunami deposits at Sendai Plain, Japan. *Geology* 40(10):887–890. doi:[10.1130/g33123.1](https://doi.org/10.1130/g33123.1)
- Goto K, Sugawara D, Ikema S, Miyagi T (2012b) Sedimentary processes associated with sand and boulder deposits formed by the 2011 Tohoku-oki tsunami at Sabusawa Island, Japan. *Sediment Geol* 282:188–198. doi:[10.1016/j.sedgeo.2012.03.017](https://doi.org/10.1016/j.sedgeo.2012.03.017)
- Gough MA, Rowland SJ (1990) Characterization of unresolved complex mixtures of hydrocarbons in petroleum. *Nature* 344:648–650. doi:[10.1038/344648a0](https://doi.org/10.1038/344648a0)
- Ikan R, Baedecker MJ, Kaplan IR (1975) Thermal alteration experiments on organic matter in recent marine sediment—II isoprenoids. *Geochim Cosmochim Acta* 39(2):187–194. doi:[10.1016/0016-7037\(75\)90170-2](https://doi.org/10.1016/0016-7037(75)90170-2)
- Jagodziński R, Sternal B, Szczuciński W, Chagué-Goff C, Sugawara D (2012) Heavy minerals in the 2011 Tohoku-oki tsunami deposits—insights into sediment sources and hydrodynamics. *Sediment Geol* 282:57–64. doi:[10.1016/j.sedgeo.2012.07.015](https://doi.org/10.1016/j.sedgeo.2012.07.015)
- Kume T, Umetsu C, Palanisami K (2009) Impact of the December 2004 tsunami on soil, groundwater and vegetation in the Nagapattinam district, India. *J Environ Manag* 90:3147–3154. doi:[10.1016/j.jenvman.2009.05.027](https://doi.org/10.1016/j.jenvman.2009.05.027)
- Mackie PR, Whittle KJ, Hardy R (1974) Hydrocarbons in the marine environment I. *n*-Alkanes in the firch of clyde. *Estuar Coast Mar Sci* 2(4):359–374. doi:[10.1016/0302-3524\(74\)90005-X](https://doi.org/10.1016/0302-3524(74)90005-X)
- Marlowe IT, Green JC, Neal AC, Brassell SC, Eglinton G, Course PA (1984) Long chain (*n*-C<sub>37</sub>–C<sub>39</sub>) alkenones in the Prymnesiophyceae. Distribution of alkenones and other lipids and their taxonomic significance. *Br Phycol J* 19:203–216. doi:[10.1080/00071618400650221](https://doi.org/10.1080/00071618400650221)
- Meyers PA, Takeuchi N (1981) Environmental changes in Saginaw Bay, Lake Huron recorded by geolipid contents of sediments deposited since 1800. *Environ Geol* 3(5):257–266. doi:[10.1007/BF02473517](https://doi.org/10.1007/BF02473517)
- Minoura K, Nakaya S (1991) Traces of tsunami preserved in inter-tidal lacustrine and marsh deposits: some examples from Northeast Japan. *J Geol* 99(2):265–287
- Minoura K, Imamura F, Sugawara D, Kono Y, Iwashita T (2001) The Jōgan tsunami deposit and recurrence interval of large-scale tsunami on the Pacific coast of northeast Japan. *J Nat Disaster Sci* 23:83–88
- Nakata T, Shimazaki K (1997) Geo-slicer, a newly invented soil sampler, for high-resolution active fault studies. *J Geogr (Chigaku zasshi)* 106(1):59–69 (in Japanese with English abstract)
- Nakaya T, Tanji H, Kiri H, Hamada H (2010) Developing a salt-removal plan to remedy tsunami-caused salinity damage to farmlands: case study for an area in Southern Thailand. *JARQ* 44(2):159–165
- Ozawa S, Nishimura T, Suito H, Kobayashi T, Tobita M, Imakiire T (2011) Coseismic and postseismic slip of the 2011 magnitude-9 Tohoku-Oki earthquake. *Nature* 475:373–376. doi:[10.1038/nature10227](https://doi.org/10.1038/nature10227)
- Peters KE, Walters CC, Moldowan JM (2007a) Biochemistry of biomarkers. In: Peters KE, Walters CC, Moldowan JM (eds) The biomarker guide, vol 1., Biomarkers and isotopes in the environment and human history petroleum exploration and Earth history Cambridge University Press, Cambridge, pp 45–71
- Peters KE, Walters CC, Moldowan JM (2007b) Source- and age-related biomarker parameters. In: Peters KE, Walters CC, Moldowan JM (eds) The biomarker guide, vol 2., Biomarkers and isotopes in petroleum exploration and Earth history Cambridge University Press, Cambridge, pp 483–607
- Pilarczyk JE, Horton BP, Witter RC, Vane CH, Chagué-Goff C, Goff J (2012) Sedimentary and foraminiferal evidence of the 2011 Tōhoku-oki tsunami on the Sendai coastal plain, Japan. *Sediment Geol* 282:78–89. doi:[10.1016/j.sedgeo.2012.08.011](https://doi.org/10.1016/j.sedgeo.2012.08.011)
- Raja R, Ghoshal Chaudhuri S, Ravisanakar N, Swarnam TP, Jayakumar V, Srivastava RC (2009) Salinity status of tsunami-affected soil and water resources of South Andaman, India. *Curr Sci* 96(1):152–156
- Richmond B, Szczuciński W, Chagué-Goff C, Goto K, Sugawara D, Witter R, Tappin DR, Jaffe B, Fujino S, Nishimura Y, Goff J (2012) Erosion, deposition and landscape change on the Sendai coastal plain, Japan, resulting from the March 11, 2011 Tohoku-oki tsunami. *Sediment Geol* 282:27–39. doi:[10.1016/j.sedgeo.2012.08.005](https://doi.org/10.1016/j.sedgeo.2012.08.005)
- Sawai Y, Fujii Y, Fujiwara O, Kamataki T, Komatsubara J, Okamura Y, Satake K, Shishikura M (2008) Marine incursions of the past 1,500 years and evidence of tsunamis at Sujin-numa, a coastal lake facing the Japan Trench. *Holocene* 18:517–528. doi:[10.1177/0959683608089206](https://doi.org/10.1177/0959683608089206)
- Sawai Y, Namegaya Y, Okamura Y, Satake K, Shishikura M (2012) Challenges of anticipating the 2011 Tohoku earthquake and tsunami using coastal geology. *Geophys Res Lett* 39:L21309. doi:[10.1029/2012GL053692](https://doi.org/10.1029/2012GL053692)
- Szczuciński W, Niedzielski P, Kozak L, Frankowski M, Ziola A, Lorenc S (2007) Effects of rainy season on mobilization of contaminants from tsunami deposits left in a coastal zone of Thailand by the 26 December 2004 tsunami. *Environ Geol* 53:253–264. doi:[10.1007/s00254-007-0639-4](https://doi.org/10.1007/s00254-007-0639-4)

- Szczuciński W, Kokociński M, Rzeszewski M, Chagué-Goff C, Cachão M, Goto K, Sugawara D (2012) Sediment sources and sedimentation processes of 2011 Tohoku-oki tsunami deposits on the Sendai Plain, Japan—insights from diatoms, nannoliths and grain size distribution. *Sediment Geol* 282:40–56. doi:[10.1016/j.sedgeo.2012.07.019](https://doi.org/10.1016/j.sedgeo.2012.07.019)
- Takada K, Nakata T, Miyagi T, Haraguchi T, Nishitani Y (2002) Handy geoslicer—new soil sampler for Quaternary geologist. *Chishitsu News* 579(1):12–18 (in Japanese with English abstract)
- Tanaka G, Naruse H, Yamashita S, Arai K (2012) Ostracodes reveal the sea-bed origin of tsunami deposits. *Geophys Res Lett* 39:L05406. doi:[10.1029/2012GL051320](https://doi.org/10.1029/2012GL051320)
- Tanaka H, Adityawan MB, Mano A (2014) Morphological changes at the Nanakita River mouth after the Great East Japan Tsunami of 2011. *Coast Eng* 86:14–26. doi:[10.1016/j.coastaleng.2014.01.002](https://doi.org/10.1016/j.coastaleng.2014.01.002)
- Tappin DR, Evans HM, Jordan CJ, Richmond B, Sugawara D, Goto K (2012) Coastal changes in the Sendai area from the impact of the 2011 Tōhoku-oki tsunami: interpretations of time series satellite images, helicopter-borne video footage and field observations. *Sediment Geol* 282:40–56. doi:[10.1016/j.sedgeo.2012.09.011](https://doi.org/10.1016/j.sedgeo.2012.09.011)
- Ünlü S, Alpar B, Altınok Y, Özer N (2012) Rapid coastal changes and tsunami impacts at the Patara Harbour (Turkey). In: Proceedings of the international conference on land–sea interaction in the coastal zone, pp 411–418
- Volkman JK, Eglinton G, Corner EDS, Forsberg TEV (1980) Long chain alkenes and alkenones in the marine coccolithophorid *Emiliania huxleyi*. *Phytochemistry* 19:2619–2622
- Yamamoto M, Polyak L (2009) Changes in terrestrial organic matter input to the Mendeleev Ridge, western Arctic Ocean, during the Late Quaternary. *Global Planet Change* 68(1–2):30–37. doi:[10.1016/j.gloplacha.2009.03.012](https://doi.org/10.1016/j.gloplacha.2009.03.012)
- Yoshii T, Imamura M, Matsuyama M, Koshimura S, Matsuoka M, Mas E, Jimenez C (2013) Salinity in soils and tsunami deposits in areas affected by the 2010 Chile and 2011 Japan tsunamis. *Pure appl Geophys* 170:1047–1066. doi:[10.1007/s00024-012-0530-4](https://doi.org/10.1007/s00024-012-0530-4)