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Repeated occurrence of surface-sediment remobilization along the landward slope of the Japan Trench by great earthquakes

Ken Ikehara^{1*} , Kazuko Usami^{1,2} and Toshiya Kanamatsu³

Abstract

Deep-sea turbidites have been utilized to understand the history of past large earthquakes. Surface-sediment remobilization is considered to be a mechanism for the initiation of earthquake-induced turbidity currents, based on the studies on the event deposits formed by recent great earthquakes, such as the 2011 Tohoku-oki earthquake, although submarine slope failure has been considered to be a major contributor. However, it is still unclear that the surface-sediment remobilization has actually occurred in past great earthquakes. We examined a sediment core recovered from the mid-slope terrace (MST) along the Japan Trench to find evidence of past earthquake-induced surface-sediment remobilization. Coupled radiocarbon dates for turbidite and hemipelagic muds in the core show small age differences (less than a few 100 years) and suggest that initiation of turbidity currents caused by the earthquake-induced surface-sediment remobilization has occurred repeatedly during the last 2300 years. On the other hand, two turbidites among the examined 11 turbidites show relatively large age differences (~ 5000 years) that indicate the occurrence of large sea-floor disturbances such as submarine slope failures. The sedimentological (i.e., of diatomaceous nature and high sedimentation rates) and tectonic (i.e., continuous subsidence and isolated small basins) settings of the MST sedimentary basins provide favorable conditions for the repeated initiation of turbidity currents and for deposition and preservation of fine-grained turbidites. The MST small basin is a suitable site for examining deep-sea turbidite paleoseismology.

Keywords: Surface-sediment remobilization, Turbidity current, Radiocarbon date, Earthquake, Japan Trench

Introduction

Deep-sea turbidites are a potential tool for submarine paleoseismology (e.g., Adams 1990; Goldfinger et al. 2007, 2012). Earthquakes are a major mechanism for the initiation of turbidity currents, although several alternative mechanisms for the initiation of turbidity currents such as large storm waves, storm surges, hyperpycnal flows (floods), rapid sediment loading, submarine groundwater discharge, volcanic eruptions, and bolide impacts have been proposed (e.g., Nakajima

2000; Goldfinger et al. 2012; Pickering and Hiscott 2015). It is well-known that earthquake-induced submarine slope failures have generated turbidity currents; e.g., the 1929 Grand Banks earthquake, NW Atlantic (Heezen and Ewing 1952), the 1954 Orleansville earthquake, Algeria (Heezen and Ewing 1955) and the 2006 Pingtung earthquake, Taiwan (Hsu et al. 2008). Thus, submarine slope failure has been considered as a major contributor for generating earthquake-induced turbidity currents. However, the temporal occurrences of bathymetric map-scale submarine slope failures shows longer (10^3 – 10^5 years) recurrence intervals at the edge of the Kumano forearc basin (Kremer et al. 2017; Lackey et al. 2018); temporal occurrences of turbidites in the nearby basins are reported at 10^2 year recurrence intervals (Ikehara 1999, 2001; Okutsu et al. 2019), which are

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similar to the recurrence intervals for interplate earthquakes along the Nankai Trough (Ando 1975). The difference in timing and scale suggests that large mappable landslides are probably not the primary source of the observed turbidites. Surface-sediment remobilization is known as another mechanism for initiation of earthquake-induced turbidites (Moernaut et al. 2017). Some evidence for surface-sediment remobilization for recent earthquakes is discussed using short-lived radionuclides such as ^{137}Cs , excess ^{210}Pb levels, and young, fragile organic matters found in earthquake event deposits (Moernaut et al. 2014, 2017; Oguri et al. 2013; Ikehara et al. 2016; McHugh et al. 2016; Mountjoy et al. 2018), and the depositional gaps in slope sediments (Molenaar et al. 2019). Molenaar et al. (2019) suggested the repeated occurrence of surface-sediment remobilization for a few cm to 12 cm from three recent strong earthquakes (2011 Tohoku-oki, 1968 Tokachi-oki and 1896 Sanriku-oki earthquakes). However, evidence for repeated occurrences of surface-sediment remobilizations has been still insufficient.

The 2011 off the Pacific coast of Tohoku (Tohoku-oki) earthquake was an interplate earthquake that occurred along the Japan Trench with an Mw 9.0 (Suzuki et al. 2011). Large ground motions and the subsequent large and destructive tsunami caused severe damage along the Pacific coast of NE Japan. The deep seafloor offshore from Sanriku was disturbed by the earthquake and by the tsunami. Abnormally high turbidity in bottom waters occurred on the Sanriku slope (Noguchi et al. 2012) and on floor of the Japan Trench (Oguri et al. 2013) immediately after the 2011 earthquake. Deep-sea event deposits were reported from the shelf to the trench floor (Arai et al. 2013; Oguri et al. 2013; Ikehara et al. 2014, 2016; Toyofuku et al. 2014; Nomaki et al. 2016; McHugh et al. 2016; Usami et al. 2017). Bao et al. (2018) indicated very small differences in the radiocarbon ages of bulk organic matter in marine sediments between the 2011 event beds and the underlying hemipelagic muds in the core of the Japan Trench. Usami et al. (2018) described repeated occurrences of earthquake-induced turbidites in sediment cores from the mid-slope terrace (MST) on the landward slope of the Japan Trench, and discussed earthquake supercycles along the Japan Trench. The turbidites reported were muddy turbidites with thin basal sand layers and thick upper turbidite mud layers.

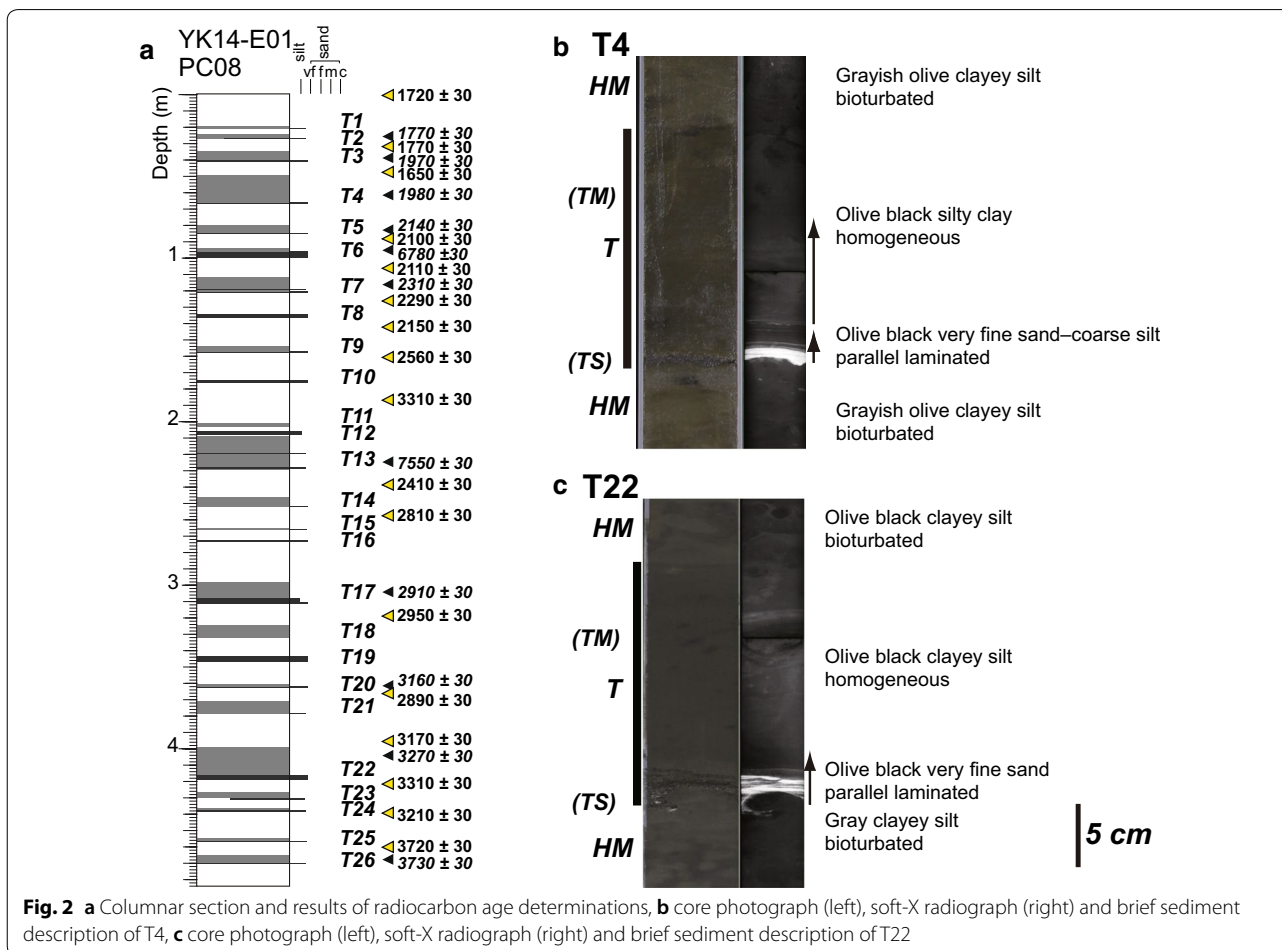
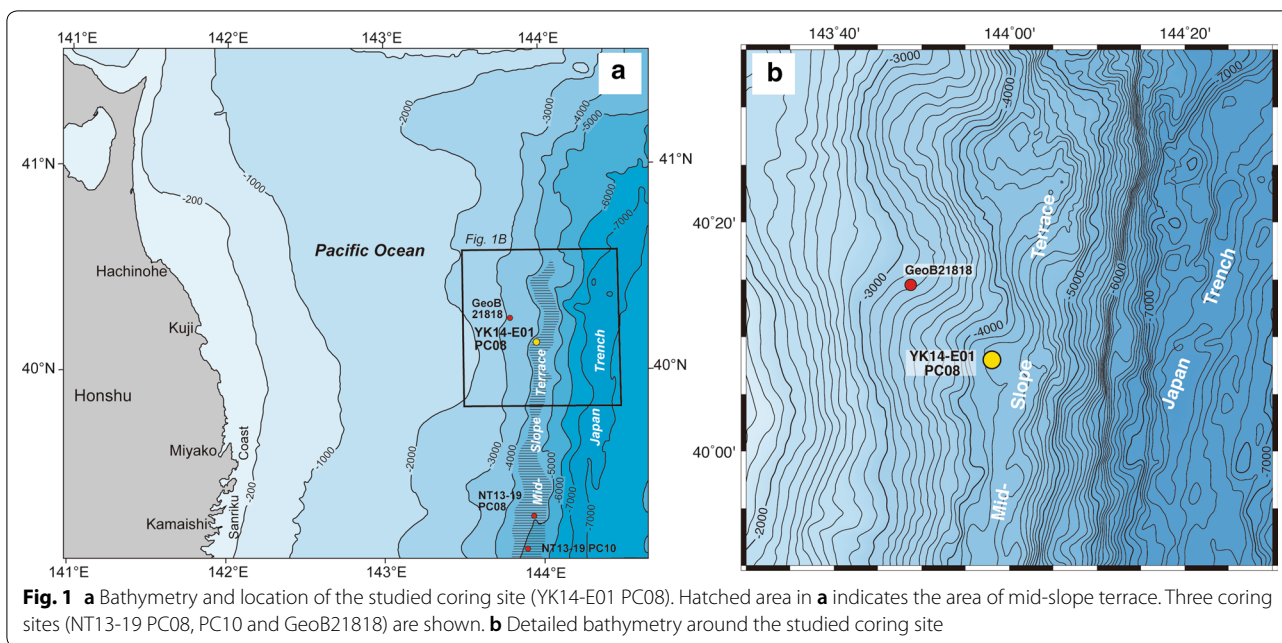
In this paper, we wish to determine the age differences between turbidite muds and the underlying hemipelagic muds in a sediment core from the MST, and to examine the repeated occurrence of surface-sediment remobilization due to past earthquakes. We discuss the importance of surface-sediment remobilization for deep-sea turbidite paleoseismology, and suitable sites for paleoseismology

investigations using turbidites caused by surface-sediment remobilization.

The mid-slope terrace (MST) and studied materials

The Pacific plate subducts beneath the Okhotsk plate at a convergence rate of 8.0–8.6 cm/year to the NW (DeMets et al. 2010). This subduction is associated with tectonic erosion, which induces forearc subsidence (von Huene and Lallemand 1990). Episodic subsidence of the upper slope forms isolated basins (Arai et al. 2014). The MST has been formed by continuous fault activity associated with the backstop interface. The flat MST surface has been maintained by the sediment supply from the slope, which has filled the depressions over the landward-dipping basement by fault activity (von Huene et al. 1980; Tsuru et al. 2002). Each depression occurred in isolation. These features trapped the sediments that were transported by gravity flows from the landward slope with few lateral migrations of sediment transport (von Huene and Culotta 1989; Tsuru et al. 2002; Usami et al. 2018). No submarine canyon connecting between shelf and the MST found off Sanriku slope suggesting that the earthquake is a major mechanism for initiation of the turbidites in the MST deposits. The surface sediments in the MST are generally diatomaceous, reflecting high diatom productivity in the surface water of this region, which has been supported by the high nutrient content of the Oyashio and the upwelling of subsurface water by mixing of the cold Oyashio waters and the warm Kuroshio waters (Saino et al. 1998). Under these conditions, the averaged sedimentation rates for the MST are high (~100–110 cm/ky), and many muddy turbidite beds are intercalated in the MST deposits (Usami et al. 2018). Several large ($M > 7.6$) earthquakes have occurred near the study site (Toda 2016). These were the 1994 Sanriku-oki ($M 7.6$) earthquake, the 1968 Tokachi-oki ($M 7.9$) earthquake, the 1933 Sanriku-oki ($M 8.3$) outer rise earthquake, the 1931 ($M 7.6$) earthquake, the 1987 ($M 7.7$) earthquake, and the 1896 Sanriku-oki ($M 8.2$) tsunami earthquake. The 2011 Tohoku-oki (Mw 9.1) earthquake occurred south of the study site.

Core YK14-E01 PC08 (position: 40° 08.0264' N, 143° 57.9590' E, water depth: 4203 m, core length: 487.4 cm) was collected from a small basin in the MST off Kuji during the YK14-E01 cruise of R/V Yokosuka (Fig. 1; <http://www.jamstec.go.jp/datadoi/doi/10.17596/0001654.html>). The core is composed of diatomaceous muds intercalated with 26 coarse event beds (Fig. 2a). Core photos and radiographs of the core with magnetic susceptibility are shown as Additional file 1: Figure S1. Each event bed is characterized by a sharp base and an upward-fining graded structure that changes from basal coarse layers to muddy upper layers (Fig. 2b, c).



Parallel- or cross-laminations are found in some basal coarse layers. Homogeneous muds without bioturbation were found above some coarse event beds. These features suggest that the event beds are considered to be “fine-grained turbidites” (Stow and Shanmugam 1980). Event (turbidite) muds are distinguished from hemipelagic muds by sedimentary structure, bulk density (X-ray transparency) and sediment color (Fig. 2b, c). The turbidite muds are originally homogeneous in structure, although they are occasionally disturbed by post-depositional burrowing, lower transparency in radiographs (suggesting higher bulk densities), and olive black colors. The hemipelagic muds are completely bioturbated, exhibit higher transparency in radiographs (suggesting lower bulk densities), and have gray–grayish olive–olive black colors. Although magnetic susceptibility of the basal coarse layer is high, no significant difference is recognized between turbidite

muds and hemipelagic muds (Additional file 1: Figure S1).

A total of 28 radiocarbon age determinations were carried out for 11 turbidite muds and for 17 hemipelagic muds (Fig. 2a and Table 1). Bulk sediment samples of approximately 5–10 cm³ from 1 to 2 cm intervals were used for measurement. We choose typical and relatively thick hemipelagic and turbidite muds for measurement to avoid mixing of hemipelagic and turbidite muds in the samples. We used bulk organic carbon for the measurements. The bulk samples were washed with acid to remove carbonates prior to the measurements. The radiocarbon dates were measured at the Accelerator Mass Spectrometer radiocarbon facility at Beta Analytics Co. Ltd. We use the conventional radiocarbon ages for discussion.

Table 1 Results of radiocarbon age determinations and age differences between turbidite muds and hemipelagic muds of the examined 11 turbidites

	Sample depth (cm)	Conventional ¹⁴ C age	δ ¹³ C	Turbidite no.	Age difference	Accession no.
1	0–2	1720 ± 30	– 20.9			Beta-485705
2	24–26	1770 ± 30	– 20.92	T2	0 (2–3)	Beta-521632
3	30–32	1770 ± 30	– 20.21			Beta-539906
4	38–40	1970 ± 30	– 19.07	T3	320 (4–5)	Beta-539907
5	45–47	1650 ± 30	– 20.7			Beta-485704
6	60–62	1980 ± 30	– 20.39	T4	330 (6–5)	Beta-536566
7	82–84	2140 ± 30	– 21.2	T5	40 (7–8)	Beta-521633
8	87–89	2100 ± 30	– 20.64			Beta-521634
9	94–96	6780 ± 30	– 20.77	T6	4670 (9–10)	Beta-521635
10	105–107	2110 ± 30	– 20.44			Beta-536567
11	115–117	2310 ± 30	– 20.73	T7	20 (11–12)	Beta-536568
12	125–127	2290 ± 30	– 20.76			Beta-536569
13	141–143	2150 ± 30	– 20.8			Beta-485703
14	160–162	2560 ± 30	– 20.75			Beta-536570
15	187.2–189.2	3310 ± 30	– 20.05			Beta-539908
16	223.2–225.2	7550 ± 30	– 21.98	T13	5140 (16–17)	Beta-536571
17	237.2–239.2	2410 ± 30	– 20.6			Beta-485702
18	254.7–256.7	2810 ± 30	– 19.34			Beta-539909
19	303.1–305.1	2910 ± 30	– 20.75	T17	– 40 (19–20)	Beta-536572
20	321.1–323.1	2950 ± 30	– 20.39			Beta-536573
21	361.1–362.1	3160 ± 30	– 20.8	T20	270 (21–22)	Beta-521636
22	366.1–368.1	2890 ± 30	– 20.8			Beta-485701
23	394.9–396.9	3170 ± 30	– 20.78			Beta-536574
24	402.9–404.9	3270 ± 30	– 20.73	T22	– 40 (24–25)	Beta-536575
25	419.9–421.9	3310 ± 30	– 19.77			Beta-539910
26	437.9–439.9	3210 ± 30	– 20.9			Beta-485700
27	459.9–461.9	3720 ± 30	– 20.71			Beta-536576
28	466.9–468.9	3730 ± 30	– 20.85	T26	10 (28–27)	Beta-536577

Results and discussion

Sediment depositional ages and turbidite occurrences

The radiocarbon dates of the hemipelagic muds generally become older with increasing the sub-bottom depths (Figs. 2a and 3 and Table 1). Although the radiocarbon dates for some horizons are slightly older than those of the underlying horizons, the relationship between the radiocarbon ages and the turbidite-free depths shows a linear relationship with a calculated averaged sedimentation rate of ~ 200 cm/ky. The radiocarbon date of the core-top hemipelagic mud (1720 ± 30 years BP) indicates that the radiocarbon date of the bulk organic matter in the hemipelagic mud has a ~ 1700 years offset from the true age. This offset is similar to those seen in the Japan Trench (~ 1600 years; Ikehara et al. 2016; Bao et al. 2018). The radiocarbon date of the hemipelagic mud near the core bottom is 3720 ± 30 years BP. Considering that the age offset is 1600 years and assuming the same sedimentation rate near the core bottom, the inferred core-bottom age is ~ 2300 years BP. Thus, our core records the late Holocene depositional history at the MST off Kuji.

A total of 26 turbidite beds (T1–T26) were recognized in core YK14-E01 PC01 (Fig. 2a). Usami et al. (2018) established a precise age model for two cores (namely, cores NT13-19 PC08 ($39^\circ 16.4448' \text{ N}$, $143^\circ 56.6842' \text{ E}$) and PC10 ($39^\circ 07.2353' \text{ N}$, $143^\circ 54.1586' \text{ E}$)) that were recovered from the MST off Kamaishi, based on tephrochronology, paleomagnetic secular variation, and short-lived radioisotope activity (^{137}Cs and excess ^{210}Pb), and

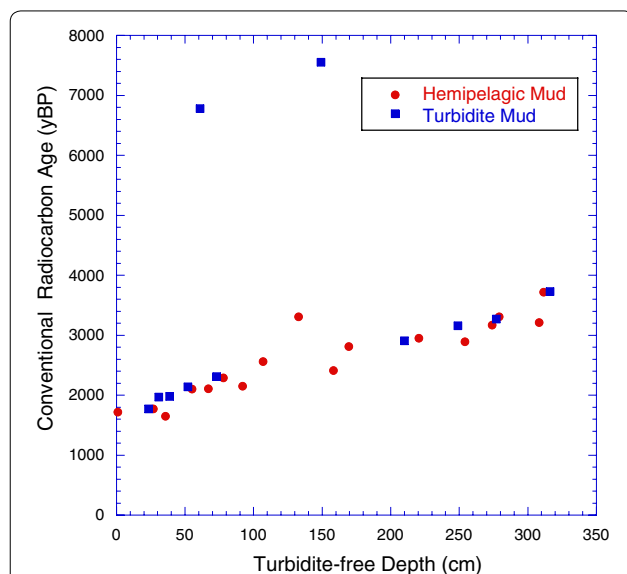


Fig. 3 Relationships between the radiocarbon ages of hemipelagic muds and turbidite-free sub-bottom depth. Ages of turbidite mud are plotted at the depths of boundaries between the overlying and underlying hemipelagic muds

also recognized ~ 12 turbidites from the last 4 ky. Our coring site is located north of their sites (Fig. 1). The turbidite frequencies are thought to be higher in our core than those reported by Usami et al. (2018). Although there is a possibility that some turbidites in our core are correlative to those of Usami et al. (2018), our present age model based on radiocarbon dates of bulk organic carbon, contains much uncertainty for the precise correlations because of the age offset between the radiocarbon dates of the bulk organic carbon and those of the planktonic foraminifera or the actual depositional dates (Ikehara 2000; Ikehara et al. 2016; Bao et al. 2018). Thus, it is necessary to conduct further chronological work such as paleomagnetic secular variation (Kanamatsu et al. 2017), for the precise correlations and depositional age determinations of each turbidite.

Age differences between paired turbidite muds and hemipelagic muds and evidence of surface-sediment remobilization

The age differences between the turbidite muds and the underlying or overlying hemipelagic muds are summarized in Table 1. They range from -40 years (T17 and T20) to 5140 years (T13). Except for T6 and T13, the differences are small and are less than a few 100 years (-40 to 330 years). The small age differences between the turbidite muds and the hemipelagic muds in the 9 turbidites among the 11 examined turbidites (Table 1) are likely evidence of surface-sediment remobilization. Bao et al. (2018) indicated small age differences between the 2011 Tohoku-oki earthquake-induced turbidites and the underlying hemipelagic muds on the Japan Trench floor. The 2011 turbidites in the nearby basin contained the short-lived radionuclides (^{137}Cs and excess ^{210}Pb) (Oguri et al. 2013; Ikehara et al. 2016), and are considered to be the results of surface-sediment remobilization. Thus, surface-sediment remobilization has occurred repeatedly due to the past great earthquakes. On the other hand, two turbidites (e.g., T6 and T13) show relatively large age differences of 4690 and 5140 years, respectively. This suggests that much larger disturbances of the sea floor, such as small submarine slope failures or older sediment mobilization might have been caused by some great earthquakes. It is interesting that the thicknesses of the two turbidites are quite different. Although the T13 turbidite is the thickest turbidite (20.7 cm thick) in this core, the T6 turbidite has a normal thickness (6 cm thick). We do not understand what differences in the magnitudes and types of earthquakes and of the ground shaking mode have caused such differences on the initiation of turbidity currents. Detailed correlation of the turbidites in the sediment cores recovered from the MST (McHugh

et al. 2016; Usami et al. 2018) is important to clarify the origin.

The age differences indicate that sediments less than a few 100 years old (on average) were remobilized and formed turbidites. The averaged sedimentation rates of turbidite-free hemipelagic muds in core YK14-E01 PC08 are calculated to be ~ 155 cm/ky, and those in cores NT13-19 PC08 and PC10 are calculated to be 72–80 cm/ky. These age differences correspond to only a few to 46 cm in the sediment thicknesses in the MST sediments. The sedimentation rates for the landward slope of the MST have not been clearly determined. Although Molenaar et al. (2019) reported the sedimentation rate of the surficial (15 cm thick) sediments in core GeoB21818 ($40^{\circ}14.790'N$, $143^{\circ}48.918'E$) on the slope at 3139 m water depth near our coring site (Fig. 1) to be 1.0–3.5 mm/year (100–350 cm/ky) from the excess ^{210}Pb activity profile, the seismic profiles of the landward slope of the Japan Trench suggest thin surface-sediment cover except for the MST (Tsuru et al. 2002; Arai et al. 2014). Therefore, much thinner surface sediments than the above-mentioned estimations were most likely remobilized and flowed downward as turbidity currents and formed the turbidites in the small basins of the MST. This idea is supported by the results of Molenaar et al. (2019), who estimated the remobilization depths on the slope to be > 2 –12 cm.

The mechanism for surface-sediment remobilization is still unclear. Oguri et al. (2016) observed resuspension of unconsolidated surface sediments due to an aftershock (M 7.3) of the 2011 Tohoku-oki earthquake on the upper slope (998 m in water depth) off Sanriku. Thus, strong ground shaking by a great earthquake might have the potential to resuspend the surface sediments. Abnormally high turbidity of the bottom water on the Sanriku slope immediately (around 1 month) after the 2011 Tohoku-oki earthquake (Noguchi et al. 2012) also suggests a high level of surface-sediment resuspension. The similar abnormally high turbidity of bottom waters was observed on the landward slope of the Nankai Trough off Kumano due to the 2004 Kii-Hanto earthquake (Ashi et al. 2014). Based on the sediment volume of the earthquake-induced event deposit (an acoustically transparent layer in sub-bottom profiles) in a slope basin and a possible sediment source area on the surrounding slope, Ashi et al. (2014) estimated that surface sediments less than a few cm thick on the slope around the basin were remobilized by the earthquake ground shaking and formed an acoustically transparent deposit in the basin. Molenaar et al. (2019) inferred centimeter-scale surface-sediment remobilization on the slope off of northern Sanriku based on the excess ^{210}Pb activity in the surface sediments. Diatomaceous sediments have lower cohesion than clayey

sediments. The diatomaceous nature of the surface sediments on the Sanriku slope might influence to easy resuspension of the surface sediments, and contribute to generate turbidity currents, which transported sediments downward.

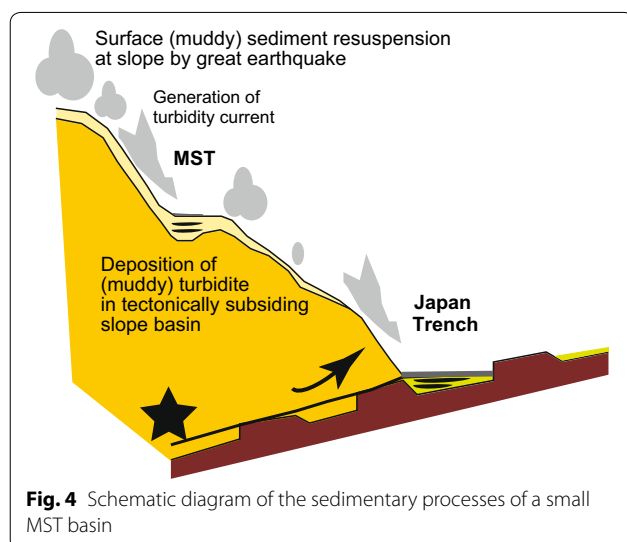
Suitable depositional settings for paleoseismology using turbidites caused by surface-sediment remobilization

From a paleoseismological point of view, it is better that the earthquake-induced turbidites are formed in the geological record by each great earthquake. Although large (bathymetry-scale) submarine slope failures are considered to be a major contributors to earthquake-induced turbidites, based on the submarine cable breaks (e.g., Heezen and Ewing 1952, 1955; Hsu et al. 2008), the reported recurrence intervals of large submarine slope failures along the Nankai Trough (Kremer et al. 2017; Lackey et al. 2018) are longer than those of the turbidites (Ikehara 1999, 2001; Okutsu et al. 2019). Thus, the surface-sediment remobilization is another possible mechanism for forming earthquake-induced turbidites. In general, fine-grained sediment is distributed widely in deep-sea environments. Fine-grained surface sediments may resuspend easily and broadly when compared with coarse-grained sediments due to their smaller grain weights. The presence of unconsolidated surface sediments on the slope when a great earthquake occurs is essential for the repeated occurrence of surface-sediment remobilization. Unconsolidated sediments should deposit and recharge before the next great earthquake. Thus, the sedimentation rates on the slope are another important factor (Ikehara and Usami, 2018). High sedimentation along the MST likely acts as a positive environmental factor for the repeated generation of turbidity currents caused by surface-sediment remobilization. High sedimentation rates also provide high preservation potential for turbidites through effective burial, thus avoiding destruction of turbidite by benthos activities.

For paleoseismological purposes, site selection for sediment coring is an important (e.g., Goldfinger et al. 2012, 2017). Here, we discuss suitable conditions for the repeated deposition of fine-grained turbidites. For deposition of fine-grained turbidites, ponding of turbid water masses may be important (e.g., Van Andel and Komar 1969; Moernaut et al. 2014; Patacci et al. 2015). Small basins or depressions (minibasins) on the slope likely acts as traps for turbidity currents coming from the landward slope. Terminal basins most likely trap the turbidity currents and form mud ponds. Formation of a 2.5 m thick mud pond (extremely turbid bottom water) by the 2004 Kii-Hanto earthquake was reported for a terminal slope basin off Kumano (Ashi et al. 2014). Continuous basin subsidence by tectonic activity associated with plate

subduction is favorable for maintaining the accommodation space in the basin. The small MST basins have been formed by continuous fault activity related to the backstop interface (von Huene et al. 1980; Tsuru et al. 2002). The tectonic movements cause the small MST basins to be suitable places for turbidite paleoseismology investigations (Fig. 4).

Connectivity between small basins is another important factor for turbidite paleoseismology. Easy connections between basins allow turbidity currents to flow long distances through canyons and channels. For example, axial turbidity currents along the Nankai Trough have flowed ~600 km from Suruga Bay to off Shikoku (Taira and Niitsuma 1986; Pickering et al. 1993). Patton et al. (2013) also discussed this problem by comparing Sumatra and Cascadia margin examples. This means that a turbidity current caused by an earthquake in a neighboring segment is able to flow into the basins of the other segments, and then, in the turbidites of a distal basin, the earthquakes that occurred in multiple segments are recorded. Under these conditions, it is difficult to understand where the rupture area of earthquake was. This is unsuitable for precise analysis of past earthquakes. Series of isolated small basins such as those on the floor of the Japan Trench axis (Ikehara et al. 2018; Kioka et al. 2019a, Kioka et al. 2019b), are considered to be better settings for turbidite paleoseismology than well-connected basins because the turbidite record in a basin represents a local record of great earthquakes. This was also discussed by Goldfinger et al. (2012) at the Cascadia margin. Small basins along the MST are isolated from each other and lateral transport among the basins by turbidity currents is thought to be small (von Huene and Culotta 1989; Tsuru et al. 2002; Usami et al. 2018).



Conclusions

We examined a sediment core recovered from the MST along the Japan Trench to find evidence of earthquake-induced surface-sediment remobilization in the past. The coupled radiocarbon dates of the turbidite muds and hemipelagic muds in the core show small age differences and suggest that the initiation of turbidity currents caused by earthquake-induced surface-sediment remobilization is a common feature and has occurred repeatedly during the last 2300 years. On the other hand, two turbidites among the 11 examined turbidites show relatively large age differences (~5000 years), indicating the occurrence of larger sea-floor disturbances such as submarine slope failures or older sediment mobilization. The sedimentological (i.e., of diatomaceous nature and high sedimentation rates) and tectonic (i.e., continuous subsidence and isolated small basin) settings of the MST basins and the nearby slopes provide favorable conditions for the repeated initiation of turbidity currents by surface-sediment remobilization due to great earthquakes and fine-grained turbidite deposition. The small MST basins are thought to be suitable sites for deep-sea turbidite paleoseismology.

Supplementary information

Supplementary information accompanies this paper at <https://doi.org/10.1186/s40623-020-01241-y>.

Additional file 1: Figure S1. Core photograph, radiograph and magnetic susceptibility profile of core YK14-E01 PC08 Section 1 was no sample. Radiographs were taken for slab samples (20 cm long and 1 cm thick). Magnetic susceptibility was measured using continuous paleomagnetic plastic cube samples (7 cc).

Abbreviation

MST: Mid-slope terrace.

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Authors' contributions

KI and KU conducted the sedimentological analyses and interpretations, and constructed the age model. TK led the cruise and sediment sampling, and conducted the magnetic susceptibility measurement. All authors read and approved the final manuscript.

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Availability of data and materials

Please contact the corresponding author for data request.

Competing interests

The authors declare that they have no competing interests.

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