Documenting large earthquakes similar to the 2011 Tohoku-oki
earthquake from sediments deposited in the Japan Trench over the
past 1500 years

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Running title: Turbidite evidence for earthquake recurrence along the Japan Trench

ABSTRACT

The 2011 Tohoku-oki earthquake and tsunami was the most destructive geohazard in Japanese history. However, little is known of the past recurrence of large earthquakes along the Japan Trench. Deep-sea turbidites are potential candidates for understanding the history of such earthquakes. Core samples were collected from three thick turbidite units on the Japan Trench floor near the epicenter of the 2011 event. The uppermost unit (Unit TT1) consists of amalgamated diatomaceous mud (30–60 cm thick) that deposited from turbidity currents triggered by shallow subsurface instability on the lower trench slope associated with strong ground motion during the 2011 Tohoku-oki earthquake. Older thick turbidite units (Units TT2 and TT3) also consist of several amalgamated subunits that contain thick sand layers in their lower parts. Sedimentological characteristics and tectonic and bathymetric settings of the Japan Trench floor indicate that these turbidites also originated from two older large earthquakes of potentially similar to the 2011 Tohoku-oki earthquake. A thin tephra layer between Units TT2 and TT3 constrains the age of these earthquakes. Geochemical analysis of volcanic glass shards within the tephra layer indicate that it is correlative to the Towada-a tephra (AD 915) from the Towada volcano in northeastern Japan. The stratigraphy of the Japan Trench turbidites resembles that of onshore tsunami deposits on the Sendai and Ishinomaki plains, indicating that the cored uppermost succession of the Japan Trench comprises a 1500-year-old record that includes the sedimentary fingerprint of the historical Jogan earthquake of AD 869.

Keywords: Turbidite; paleoseismology; tephra; Japan Trench; Holocene

1. Introduction

The 2011 Off the Pacific Coast of Tohoku earthquake (2011 Tohoku-oki) earthquake was one of the largest earthquakes in recorded history and had a moment magnitude (M_w) greater than 9 (Suzuki et al., 2011). The earthquake generated a large destructive tsunami that hit the Pacific coast of NE Japan and caused extensive damage. Based on tsunami waveform inversion, Fujii et al. (2011) suggested that the tsunami was generated by a deep inter-plate slip and large displacement near the Japan Trench axis. Yokota et al. (2011) reported that the shallow slip along the plate boundary fault contributed significantly to the destructive power of the tsunami. Fujiwara et al. (2011) concluded that displacement of the seafloor near the earthquake epicenter resulted in bathymetric changes of as much as 50 m in height. Propagation of tectonic displacement extended to the trench axis (Kodaria et al., 2012) and triggered a major rotational slump on the lowermost trench slope (Strasser et al., 2013). **However, extending of the slip to the whole rupture area of the 2011 Thoku-oki earthquake along the Japan Trench has not been fully understood.** Large amounts of sediment resuspension and redeposition related to the 2011 earthquake and tsunami are documented across the entire subduction zone margin from the shallow shelf to the >7-km-deep trench floor (Noguchi et al., 2012; Arai et al., 2013; Oguri et al., 2013; Ikehara et al., 2014; Toyofuku et al., 2014; Tamura et al., 2015).

Such large earthquakes have occurred repeatedly not only at the Japan Trench but also at other subduction zones such as the Aleutian, Sumatra and Chilean trenches, yet we have only a limited understanding of the earthquake recurrence interval and rupture mode variability in such settings. Before the 2011 Tohoku-oki earthquake, paleoseismic studies of the Japan Trench focused solely on onshore tsunami deposits. Minoura and Nakaya (1991) and Sawai et al. (2012) reported widespread onshore

tsunami deposits on the Sendai plain that are correlative to the historical Jogan tsunami of AD 869.

Despite the advances made in previous studies of onshore tsunami deposits, information on the source areas (epicenters) of the tsunamis remains limited. Onshore tsunami deposits in Japan, such as those along the Sanriku and Hokkaido coasts (Kon'no et al., 1961; Nanayama et al., 2003), could also have been formed by a far-field tsunami such as the 1960 Chilean tsunami. Deep-sea turbidites, on the other hand, have been used to reconstruct the history of earthquakes along subduction zone margins (e.g., Adams, 1990; Goldfinger et al., 2003, 2008, 2012; Noda et al., 2008; Goldfinger, 2011; Patton et al., 2013, 2015; Atwater et al., 2014; Pouderoux et al., 2014). These previous studies have shown that earthquakes are a major trigger mechanism for submarine slope failure and sediment resuspension. Strong ground motion on the sea floor associated with an earthquake causes increased pore pressure in sediments and reduced sediment strength, leading to slope failure and the formation of gravity flow deposits such as debrites and turbidites at the base of the slope. Although fundamental challenges exist in studies of turbidite paleoseismology, such as site characterization and turbidite records (Sumner et al., 2013; Atwater et al., 2014), numerous core analyses based on high-resolution bathymetric and backscatter data provide reliable history of past earthquakes (Goldfinger et al., 2012, 2014; Patton et al., 2015). Thus, deep-sea turbidites are potentially an indicator of the occurrence of large earthquakes in the past. However, there have been no studies on the recurrence history of deep-sea turbidites along the Japan Trench.

In this paper, we present new data from two rapid-response cruises by the R/V *Mirai* (MR12-E01) and the R/V *Sonne* (SO219A) to the Japan Trench floor, 140 km seaward of the 2011 Tohoku-oki earthquake epicenter (Fig. 1A and B). Based on these data, we report on the occurrence of

major Holocene deep-sea turbidites, discuss their relation to seismic events, and infer the recurrence interval of large earthquakes along the Japan Trench.

2. Japan Trench

The Japan Trench is a plate boundary, where the Pacific Plate is subducting beneath the Okhotsk Plate with its convergent rate of 8.0 to 8.6 cm/year to NW direction (DeMets et al., 2010). The axis of Japan Trench has N-S to NNE-SSW direction from triple junction among the Pacific, Philippine Sea and Okhotsk plates at south to junction with the Kuril Trench at north. Water depth of the axis becomes deeper southward from ~6800 m at north to >7500 m at central and south. On the subducting Pacific Plate, typical horst-graben structure is observed. There is no typical forearc basin along the Japan Trench, but subduction erosion along the trench makes tectonic subsidence (von Huene and Lallemand, 1990) and forms the gently sloped upper slope terrace with some isolated basins (Arai et al., 2014). The average slope angle of the lower slope is ~5 degree (von Huene and Lallemand, 1990). No canyon system that connect shelf with trench floor at the central Japan Trench near the epicenter of the 2011 Tohoku-oki earthquake, although a few canyon systems are observed at the northern Japan Trench.

The northeastern Pacific coast and slope of Japan are characterized by high primary productivity due to the mixing of warm Kuroshio and cold Oyashio waters (Saino et al., 1998). Diatom is a major contributor of the primary productivity in the surface water. Reflecting the high export flux of diatom frustules, diatomaceous silt to silty clay and diatom ooze distributes on the lower slope and trench floor, whereas calcareous and diatomaceous clay with abundant clastic and pumiceous grains distributes on the upper slope (Mann and Muller, 1980; Arita and Kinoshita, 1984; Ikehara et al., 2013).

3. Materials and methods

We collected five piston cores (PC01, -03, -04, -05, and -06) during the R/V *Mirai* MR12-E01 cruise and three gravity cores (GeoB16431-1, 16433-1, and 16444-1) during the R/V *Sonne* SO219A cruise (Table 1 and Fig. 1B). Short gravity cores (PL01, -03, -04, -05, and -06) were collected using a pilot corer of the *Mirai* piston core system. Cores were split laterally onboard and physical descriptions of the cores were made. Smear slide observations were conducted to determine sediment composition using a polarized light microscope. Soft X-ray radiographs were taken for slab samples (1 cm thick) to observe detailed sedimentary structures. Bulk density and magnetic susceptibility profiles were obtained using multi-sensor core loggers onboard R/V *Mirai* for the piston (PC) and short gravity (PL) cores, and at MARUM (University of Bremen) for the gravity cores. The major element composition of volcanic glass shards was analyzed using scanning electron microscopy coupled with energy dispersive X-ray spectroscopy (SEM-EDS) at Fukushima University to facilitate the subsequent identification and correlation of tephra layers found in the cores with terrestrial and/or marine tephras of known age. To complete the correlations, a newly collected volcanic ash sample (Towada [To-a] tephra) from the Sendai plain was also analyzed. To determine the depositional ages of the cores, radiocarbon age determinations using bulk organic carbon in the sediments were carried out for 24 horizons in two cores (PC03 and PC06) collected during the MR12-E01 cruise. Radiocarbon dating using accelerated mass spectrometry (AMS) was conducted at Beta Analytic Co. Ltd. For measurements of radioactive cesium and lead, sediments from PL03 and PL06 were sampled at a resolution of 1 cm and measured using a gamma spectrometer at Hokkaido University at a resolution of 1–5 cm.

4. Sediment lithology and age

4.1. Sediment lithology

Total 8 sediment cores obtained for this study were composed primarily of diatomaceous clay and ooze (Fig. 1C). In all cores, three fining-upward units (Units TT1 to TT3 in descending stratigraphic order), ranging in thickness from tens of centimeters to a few meters, occur above a sharp erosional surface. Internally, these units are composed of a few to several amalgamated fining-upward subunits (Fig. 2). Sandy layers in each subunit have grain sizes ranging from coarse silt to fine sand and exhibit parallel- or cross-lamination with a sharp and erosional basal contact. Some sandy layers show positive peaks in bulk density and magnetic susceptibility (Fig. 1C). The muddy layers of each subunit thicken upwards, resulting in a fining-upward stratigraphy with an upward decreasing trend in sediment bulk density and magnetic susceptibility (Fig. 1C). Muddy layers are generally diatomaceous and homogeneous without evidence of bioturbation but occasionally contained calcareous nanoplankton. These units have sedimentary structures similar to those of fine-grained turbidites (subdivision T0–T8) described by Stow and Shanmugam (1980), and to those of the upper part of classical turbidites (division Tc–Te) described by Bouma (1962). Muddy layers in Unit TT3 commonly contain a large suite of calcareous nanofossils. In addition to the three major turbidite units TT1–TT3, there are several thin single-layered and fining-upward turbidite layers with a sharp erosional base. These thin turbidites are intercalated with the bioturbated diatomaceous clay and ooze that represents the continuous background sedimentation of hemipelagic mud.

4.2 Tephra correlation, depositional age and sedimentation rates

A volcanic ash layer is intercalated with the hemipelagic diatomaceous mud between turbidites TT2 and TT3. To identify and correlate the tephtras that occur between the thick turbidite Units TT2 and TT3 in cores MR12-E01 PC03, -04, -06, SO219A-GeoB16431-1, -16433-1, and -16444-1, the major element composition of several volcanic glass shards in each sample was measured by SEM–EDS at Fukushima University. Results are listed in Table 2 and shown in Fig. 3. The chemical composition of glass shards within the volcanic ash layer is similar in all cores, suggesting that the ash originated from the Towada volcano in NE Japan. The chemical composition of the volcanic ash layers is also similar to that of the late Holocene Towada-a tephra (To-a) on the Sendai plain, which was emplaced at AD 915 (Machida and Arai, 2003) (Fig. 3 and Table 2).

Correlation of the TT2 and TT3 volcanic ash layers with the To-a tephra is supported by Holocene radiocarbon ages of bulk organic carbon from sediments in piston cores PC03 and PC06 (Fig. 4 and Table 3). However, the radiocarbon ages are ~2000–3000 years older than the age of the To-a tephra layer. Given the robust To-a tephra correlation, we conclude that the radiocarbon ages of bulk organic carbon were affected by contamination by older organic carbon. Nevertheless, all of the measured ages are younger than 10,000 years BP (before present), thus indicating a Holocene age. Radiocarbon ages of turbidite mud are older than those of hemipelagic mud (Table 3 and Fig. 4).

Based on the stratigraphic depths and eruption age of the To-a tephra, the average sedimentation rates including the turbidite beds in the study area range between 100 and 440 cm/kyr., and those excluding the turbidite beds range between 80 and >300 cm/kyr. These rates are much higher than those including the turbidite beds measured around the Japanese islands, such as ~15 cm/kyr in the

Sanriku forearc basin (Ikehara et al., 2013), 40–100 cm/kyr at sites located south of the Hokkaido forearc basin (Ikehara et al., 2006), and 20–212 cm/kyr in forearc basins along the Nankai Trough (Omura et al., 2012).

5. The 2011 Tohoku-oki seismo-turbidite

Turbidite Unit TT1 occurs in the uppermost part of the cores. The undisturbed pilot cores of PC01, -03, -04, -05, and -06 (identified here as PL01, -03, -04, -05 and -06, respectively) reveal that the thickness of Unit TT1 ranges from 30 to 60 cm. All Unit TT1 deposits are composed of diatomaceous clay and consist of fining-upward subunits. The brownish color of the sediment and the lack of bioturbation distinguishes the turbidite from bioturbated and grayish hemipelagic mud that underlies the turbidite. A thin (0.5–1.0 cm) very fine sand to coarse silt layer occurs above a sharp erosional base that cuts into the underlying hemipelagic diatomaceous clay (Fig. 5). In some cores (PL03 -04 and -05), the underlying hemipelagic clay was dark brownish in color suggesting the past surface oxidized layer. Several fining-upward subunits were observed. Parallel laminations were observed in the lower part of some subunits. Light-colored diatom ooze usually occurs at the top of each subunit. These structures are basically identical to those reported by Oguri et al. (2013) from the nearby location of PC01.

Radioactive ^{137}Cs concentrations were measured at the sediment surface and within the lower subunits (Fig. 5). Excess ^{210}Pb concentrations increase downward and show a broad peak just above the basal sand layer. Both ^{137}Cs and excess ^{210}Pb were also detected in the hemipelagic diatomaceous clay below Unit TT1. Detection of ^{137}Cs suggests that the sediments were deposited after the start of atmospheric nuclear testing (AD 1952). In contrast, ^{134}Cs was not detected in the sediments, suggesting

that deposition occurred before the accident at the Fukushima No. 1 Nuclear Power Plant in 2011. There is no hemipelagic sediment above Unit TT1. Taken together, the data and observations indicate that turbidite Unit TT1 was deposited immediately after the 2011 Tohoku-oki earthquake as a result of sediment remobilization and turbidity current flow along the slope of the Japan Trench. The lower trench slope is mostly covered by diatomaceous clay and ooze, whereas the upper slope comprises calcareous and diatomaceous clay with abundant clastic grains (e.g., Mann and Muller, 1980). High excess ^{210}Pb concentrations in the diatomaceous clay of Unit TT1 suggest that the young surface sediments on the lower slope were mobilized by the earthquake, which thus represents the most likely origin of Unit TT1. Noguchi et al. (2012) concluded from slope stability evaluations that a surficial submarine landslide was the likely cause of the high turbidity in the bottom waters near the epicenter of the 2011 Tohoku-oki earthquake. Oguri et al. (2013) also reported high turbidity in the bottom water in the Japan Trench, and absence of benthic organisms such as cnidaria, annelida or holothuria, which common inhabit the hadal zone like the Japan Trench floor (Ohta and Laubier, 1987). Therefore, ground motion on the lower trench slope during the 2011 Tohoku-oki earthquake was strong enough to cause sediment instability, leading to turbidite deposition in the Japan Trench.

6. Possible past earthquakes and correlation with onshore tsunami deposits

The high sedimentation rates in the Japan Trench mean that earthquake-triggered turbidites are preserved in the sedimentary record. Rapid and continuous sediment accumulation protects turbidite deposits from physical erosion and biological disturbance. The Japan Trench floor is composed of a series of small isolated basins that formed via the development of horst and graben topography associated

with subduction of the Pacific Plate. As the deepest depression in the area, the Japan Trench floor is considered to be a sediment sink and is a terminus of sediment transport. There are no margin-wide canyon systems that connect shore or shelf areas with the deep-sea trench. High primary (diatom) productivity in the Sanriku area (Saino et al., 1998) provides a large influx of fresh biogenic particles to the sea floor. The extremely high sedimentation rates in the Japan Trench are thus supported by topographic and oceanographic conditions. The frequent occurrence of earthquakes with moderate to small magnitudes along the Japan Trench causes downslope sediment transport into the trench (Itou et al., 2000) and contributes to high sedimentation rates and the transport of old organic matter

The cores analyzed in the present study contain three thick turbidite units (Fig. 6). As discussed above, the uppermost Unit TT1 **most likely** formed as a consequence of the 2011 Tohoku-oki earthquake. Units TT2 (30–180 cm thick) and TT3 (60–240+ cm thick) contain several amalgamated subunits with thicker and coarser sand layers than those of Unit TT1. Each subunit in Unit TT2 consists of diatomaceous clay with thick basal layers of very fine sand. Diatomaceous turbidite mud in Unit TT3, on the other hand, also contains calcareous nanofossils. The Japan Trench floor is >7500 m deep and is located far below the carbonate compensation depth (CCD; ~4000–4500 m in the NW Pacific; Berger et al., 1976). Based on this observation, we interpret that during the deposition of Unit TT3, a large amount of sediment was supplied to the Japan Trench from slope environments located at water depths of <4000 m. Given the large source area of the sediment in Unit TT3 and that Units TT2 and TT3 can be identified in event deposits in multiple trench floor basins separated by >50 km along the strike of the trench, we infer that Units TT2 and TT3 are analogous to Unit TT1 and thus also provide evidence of large megathrust earthquakes in the Japan Trench.

The depositional ages of Units TT2 and TT3 are constrained by the To-a tephra that is intercalated between them. Based on our turbidite stratigraphy and age controls, we infer that large earthquakes occurred before and after deposition of the To-a tephra (AD 915). These earthquakes may have been similar to the 2011 Tohoku-oki earthquake with respect to the intensity of offshore ground motion that remobilized sediment from the landward slope and transported a huge amount of sediment to the trench by turbidity currents. Of note, the turbidite stratigraphy in the Japan Trench is similar to the onshore tsunami deposit stratigraphy on the Sendai and Ishinomaki plains (Sawai et al., 2012), as inferred by using the To-a tephra horizon in each section as a marker horizon (Fig. 6). The onshore tsunami deposit that occurs immediately below the To-a tephra was correlated (based on radiocarbon ages) with the historical “Jogan” tsunami (AD 869) deposits (Minoura and Nakaya, 1991; Sawai et al., 2012). Based on this stratigraphic correlation, we attribute the deposition of turbidite Unit TT3 in the Japan Trench to the Jogan earthquake of AD 869. Numerical simulations suggest that the “Jogan” tsunami source was a seismic event similar to that of the 2011 Tohoku-oki earthquake (Namegaya and Satake, 2014). This result from tsunami modeling supports our independent conclusion, based on seismo-turbidite stratigraphy, that the Unit TT3 turbidite was formed by the large “Jogan” earthquake, which caused similar offshore effects to those resulting from the 2011 Tohoku-oki earthquake. Onshore, additional sandy tsunami deposits were found above the To-a tephra on the Sendai and Ishinomaki plains, and were correlated to either the “Keicho” tsunami (AD 1611) or a tsunami that occurred in the 14th century (Sawai et al., 2012). Historical documents indicate that the “Kyotoku” tsunami (AD 1454) was huge and resulted in widespread inundation along the Pacific coast of Tohoku (Namegaya and Yata, 2014). Sawai et al. (2015) suggested that the “Kyotoku” tsunami was another earthquake originating near the epicenter of

the 2011 Tohoku-oki earthquake. Although the tsunami sources for these two onshore event deposits have yet to be conclusively identified, our turbidite stratigraphy and the potentially correlative Unit TT2 in the Japan Trench reveals that these two tsunami sources also occurred near the epicenter of the 2011 Tohoku-oki earthquake in the Japan Trench. To confirm the past two tsunami sources, spatial distributions of Units TT2 and TT3 along the Japan Trench floor should be clarified.

7. Conclusions

Sediment cores collected from a small basin in the Japan Trench near the epicenter of the 2011 Tohoku-oki earthquake reveal three turbidite units of several tens of centimeters to a few meters thick (Units TT1 to TT3). High sedimentation rates in the Japan Trench (~1.0–4.4 m/kyr) resulted in the excellent preservation of earthquake-triggered turbidite deposits. The uppermost turbidite, Unit TT1, was most likely formed by the 2011 Tohoku-oki earthquake as a result of strong ground motions that triggered shallow subsurface instability on the lower slope of the Japan Trench floor. A volcanic ash layer that occurs between Units TT2 and TT3 is correlated with a previously dated historical ash layer (To-a tephra) erupted from Towada volcano in AD 915. The turbidite stratigraphy in the Japan Trench is similar to that of onshore tsunami deposits on the Sendai and Ishinomaki plains. These observations indicate that at least three large earthquakes have occurred near the epicenter of the 2011 Tohoku-oki earthquake during the past 1500 years. Turbidite Unit TT3 below the To-a tephra represents the largest event in terms of sediment remobilization, as indicated by the incorporation of calcareous nanofossil-bearing sediment from slope environments (<4000 m water depth) into turbidites transporting sediments into the 7500-m-deep Japan Trench. Unit TT3 is correlative to the onshore “Jogan” tsunami deposits dated at AD

273 869.

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416

417 **Figure and table captions**

418 Figure 1. A: Location of the study area. B: Bathymetry and sampling locations of cores retrieved by the
419 R/V *Mirai* MR12-E01 and R/V *Sonne* SO219A cruises. C: Stratigraphic sections and physical properties
420 of cored materials.

421

422 Figure 2. Internal structures of Unit TT3 (Core GeoB16433-1). T0-T8 indicates subdivision of
423 fine-grained turbidite by Stow and Shanmugam (1980).

424

425 Figure 3. Major geochemical characteristics of volcanic glass shards from the volcanic layer between
426 Units TT2 and TT3, and comparison with the correlative To-a tephra (see Data Repository for a
427 description of methods).

428

429 Figure 4. Depth distribution of radiocarbon ages for cores MR12-E01 PC03 and PC06 (yBP = years
430 before present).

431

432 Figure 5. Sedimentological and radiological characteristics of the 2011 Tohoku-oki seismo-turbidites.

433

434 Figure 6. Stratigraphic correlation of the cores retrieved by the R/V *Mirai* MR12-E01 and R/V *Sonne*
435 SO219A cruises.

436

437 Table 1. List of the coring locations

438

439 Table 2. Major element geochemistry of volcanic glass shards.

440

441 Table 3. Results of radiocarbon age determinations using bulk organic carbon in sediments.

Fig. 1 Ikehara et al.

Fig. 3 Ikehara et al.

Fig. 4 Ikehara et al.

Fig. 5 Ikehara et al.

Fig. 6 Ikehara et al.

Cruise	Core	Latitude		Longitude		Water Depth (m)
MR12-E01	PC01 (PL01)	38°	05.154′	143°	59.460′	7546
	PC03 (PL03)	38°	05.992′	143°	59.978′	7541
	PC04 (PL04)	38°	01.435′	144°	00.236′	7554
	PC05 (PL05)	38°	04.493′	143°	59.427′	7517
	PC06 (PL06)	38°	03.014′	144°	00.431′	7541
SO219A	GeoB 16431-1	38°	00.177′	143°	59.981′	7542
	GeoB 16433-1	38°	07.843′	144°	00.135′	7525
	GeoB 16444-1	37°	42.017′	143°	52.377′	7529

Table 1 Ikehara et al.

Core	SiO ₂		TiO ₂		Al ₂ O ₃		FeO*		MnO		MgO		CaO		Na ₂ O		K ₂ O		Number
	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.	
MR12-E01 PC03	75.79	0.27	0.38	0.10	13.27	0.16	2.00	0.10	0.16	0.10	0.45	0.08	2.12	0.11	4.20	0.13	1.64	0.10	15
MR12-E01 PC04	75.89	0.22	0.39	0.12	13.19	0.13	1.98	0.12	0.11	0.10	0.48	0.06	2.12	0.09	4.15	0.12	1.69	0.04	15
MR12-E01 PC06	75.96	0.17	0.34	0.09	13.19	0.09	1.91	0.19	0.10	0.07	0.46	0.06	2.13	0.05	4.21	0.11	1.70	0.06	13
SO219A-16431	75.96	0.21	0.36	0.10	13.24	0.16	2.02	0.18	0.09	0.08	0.46	0.07	2.14	0.09	4.06	0.18	1.67	1.06	13
SO219A-16433	75.71	0.19	0.39	0.09	13.24	0.14	1.94	0.14	0.13	0.10	0.52	0.08	2.17	0.10	4.23	0.09	1.69	0.05	12
SO219A-16444	75.72	0.32	0.38	0.07	13.25	0.11	1.98	0.26	0.12	0.12	0.49	0.08	2.14	0.07	4.23	0.09	1.68	0.08	14
Sendai plain	75.80	0.21	0.40	0.09	13.29	0.14	1.93	0.14	0.08	0.06	0.48	0.07	2.13	0.10	4.22	0.08	1.66	0.05	24

FeO*: total iron caluculated as FeO

Table 2 Ikehara et al.

Core	Sample ID	Depth (cm)	Conventional radiocarbon age	Sediment type
MR12-E01 PC03	PC3 3	39.0-41.0	2640 ± 30	HP
	PC3 5	78.4-80.4	3040 ± 30	HP
	PC3 8	138.4-140.4	3150 ± 30	HP
	PC3 10	178.8-180.8	5370 ± 40	HP?
	PC3 15	276.8-278.8	5690 ± 30	TM
	PC3 20	377.1-379.1	6130 ± 30	TM
	PC3 24	456.5-458.5	3480 ± 30	HP
	PC3 25	469.5-471.5	4390 ± 30	HP
	PC3 31	577.0-579.0	2930 ± 30	HP
	PC3 35	657.0-659.0	3580 ± 30	HP
	PC3 41	777.5-779.5	8920 ± 40	TM
	PC3 46	878.2-880.2	7830 ± 40	TM
MR12-E01 PC06	PC6 4	49.0-51.0	3470 ± 30	HP
	PC6 6	89.0-91.0	6160 ± 30	TM
	PC6 9	140.0-142.0	2960 ± 30	HP
	PC6 10	160.0-162.0	3550 ± 30	HP
	PC6 13	220.0-222.0	3460 ± 30	HP
	PC6 18	320.2-322.2	4110 ± 30	HP
	PC6 23	420.2-422.2	4230 ± 30	HP
	PC6 28	524.8-526.8	5250 ± 30	HP
	PC6 33	628.3-630.3	5900 ± 30	HP
	PC6 38	734.3-736.3	6200 ± 30	HP
	PC6 45	878.3-880.3	6480 ± 40	HP
	PC6 48	919.2-921.2	6820 ± 40	HP

Sediment type: HP, hemipelagic diatomaceous mud; TM, turbidite mud

Table 3 Ikehara et al.