Reconstruction of Tsunami Occurrence on Okushiri Island, Southwestern Hokkaido, Japan

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Reconstruction of tsunami occurrence on Okushiri Island, southwestern Hokkaido, Japan

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Abstract

The eastern margin of the Japan Sea is located along an active convergent boundary between the North American and Eurasian tectonic plates. Okushiri Island, which is situated off the southwest coast of Hokkaido, is located in an active tectonic zone where many active submarine faults are distributed. Studying the records of past tsunamis on Okushiri Island is important for reconstructing the history and frequency of fault activity in this region, as well as the history of tsunamis in the northern part of the eastern margin of the Japan Sea. Five tsunami deposit horizons have been identified previously on Okushiri Island, including that of the 1741 tsunami, which are interbedded in the coastal lowlands and Holocene terraces. However, these known tsunami deposits date back only ~3,000 years. A much longer record of tsunami occurrence is required to consider the frequency of submarine fault activity. In this study, we cored from 7 to 25 m depth in the Wasabiyachi lowland on the southern part of Okushiri Island, where previous studies have confirmed the presence of multiple tsunami deposits on peat layer surfaces. The results indicate that the Wasabiyachi lowland comprises an area that was obstructed by coastal barriers between the lowland and the coast at ~8.5 ka and consists of muddy
sediment and peat layers formed in lagoons and floodplains, respectively. In addition, event deposits and 15 tsunami horizons were observed among the turbidites and peat layers, dating back as far as 3,000 years. Combined with previous findings, Okushiri Island has sustained 20 tsunami events between ~7.5 ka and the present. These findings are critical for investigating the activities of submarine faults off the southwestern coast of Hokkaido, as well as for determining tsunami risks along the coast of the Japan Sea between North Tohoku and Hokkaido.

Keywords

- tsunami deposit
- tsunami recurrence
- Okushiri Island
- Hokkaido
- Japan Sea

Main Text

1. Introduction

The 2011 Tohoku-Oki earthquake produced a tsunami that caused severe damage to the Pacific coast of the Tohoku region (Japan Meteorological Agency, 2012). Following the tsunami disaster, local governments along the coast of the Japan Sea have
evaluated their tsunami risks by predicting tsunami heights in each region and by
reconstructing tsunami occurrence histories. In recent years, tsunamis in the Japan Sea
caused by the 1983 Middle Japan Sea earthquake, and the 1993 Hokkaido Nansei-Oki
earthquake have caused severe damage (Fig. 1). Among these, the 1983 Middle Japan
Sea earthquake (Mj=7.7, Mw=7.7) that occurred off the coast of the Tsugaru region of
Aomori Prefecture produced a tsunami with high watermarks of over 10 m in the coastal
area that extended from Happo Town to the right bank of the Yoneshiro River in Akita
Prefecture, with a maximum upstream height of 14.9 m in Minehama, Happo Town.
Tsunamis have claimed over 100 lives in Akita and Aomori Prefectures (Japan
Meteorological Agency, 1984, Aomori Prefecture, 1984; Shuto, 1984; Abe and Ishii,
1987). The 1993 Hokkaido Nansei-Oki earthquake (Mj=7.8, Mw=7.7) occurred off the
northwest coast of Okushiri Island, Hokkaido. High watermarks on Okushiri Island from
the tsunami were 10–20 m or higher at some locations. At Aonae, located at the southern
end of Okushiri Island, the tsunami arrived from the west and traveled northeast, with
maximum heights of more than 7–10 m. As a result, 198 lives were lost on Okushiri Island,
of which 109 were victims of the tsunami in the Aonae district (Geological Survey of
As the tsunami risks along the coast of the Japan Sea are currently being re-evaluated, the Committee for Technical Investigation on Large-Scale Earthquakes in the Sea of Japan (2014) (hereafter abbreviated as the Committee of the Japan Sea) has summarized the distribution of active submarine faults throughout the Japan Sea and created a rectangular model of tsunami sources based on previously collected seafloor geophysical data. Moreover, data relating to tsunamis produced by historical earthquakes in the Japan Sea and research on tsunami deposits were compiled and assessed to reconstruct the historical record of tsunamis for each region (Committee of the Japan Sea, 2014). Furthermore, local governments along the coast of the Japan Sea have estimated the local tsunami inundation, the tsunami risk for each region, and potential damage based on tentative modeling. However, compared to the Pacific coast, there are fewer historical records of earthquakes and tsunamis along the coast of the Japan Sea, making it difficult to clarify tsunami occurrence in the Japan Sea that can serve as a basis for tsunami risk evaluation.

Accordingly, tsunami occurrences have been investigated using deposits not
only along the coast of the Japan Sea, but also further off the Pacific coast of the Tohoku region. However, reconstructing past tsunami occurrences, including events prior to 2011, have been limited to tsunamis that occurred ~2–3 ka (Minoura et al., 1987; Minoura and Nakaya, 1990, 1991; Nanayama et al., 2000; Nishimura et al., 1999; Nishimura et al., 2000; Kamataki et al., 2015, 2016, 2017, 2018a, b, 2019; Kase et al., 2016; Kawakami et al., 2015; Okada et al., 2018, 2019). Because the period between events is short in terms of the frequency of fault activity along the coast of the Japan Sea (approximately once every few thousand years), it is necessary to investigate strata that date beyond a few thousand years ago in addition to widely distributed tsunami deposits (Kawakami et al., 2017b; Urabe, 2019; Takashimizu et al., 2020).

In this study, we investigated the Wasabiyachi lowland at the southern end of Okushiri Island, Hokkaido, to observe and analyze tsunami occurrences between Hokkaido and the North Tohoku coast prior to a few thousand years ago. The Wasabiyachi River has a small drainage area that flows into Aonae Bay. Peat layers were deposited on the surface of the Wasabiyachi lowland. According to Kase et al. (2016) and Kawakami et al. (2017a, b), these peat layers (~0–2 m depth) include four to five
interbedded medium-grained sand layers that exhibit erosive bases and weak normally
graded structures. These sand layers have been determined to be tsunami-induced
deposits based on landward changes in grain size and layer thickness, as well as owing to
the paleocurrent, distribution, and characteristics of microfossils in the sand layers. The
estimated ages of the tsunami deposits observed on Okushiri Island are 1741 C.E., 0.8–
0.9 ka, 1.5–1.6 ka, 2.4–2.6 ka, and 2.8–3.1 ka (Kawakami et al. 2017a, b).

Accordingly, we cored from 7 to 25 m at five of the sites surveyed by Kase et
al. (2016) and Kawakami et al. (2017a, b) to examine tsunami-generated deposits older
than 3 ka. We identified event deposits related to 20 tsunami horizons, dating back to ~7
ka, including the five tsunami deposits reported by Kase et al. (2016). This constitutes the
first reconstruction of tsunami occurrence along the coast of the Japan Sea off
southwestern Hokkaido. These findings are important for further extended
reconstructions of tsunamis in the Japan Sea from the coast of Niigata Prefecture to North
Tohoku.
2. Geologic and topographic setting

2.1. Okushiri Island

The area between the coastal region along the Japan Sea side of northeastern Japan contains many reverse faults and is known as the Japan Sea Eastern Margin Mobile Belt (Taira, 2002). The eastern margin of the northern Japan Sea is located at the boundary between the North American and Eurasian (Amurian) tectonic plates (Seno et al., 1996; Isozaki et al., 2010), and a compressive stress field has developed in this region (Seno, 1999; Okamura, 2000). Therefore, many active onshore and submarine faults are located within a short distance (~200–250 km) from the coast to the offshore area of the northern Tohoku to Hokkaido region (Fig. 1).

Okushiri Island is located on Okushiri Ridge, which extends N–S in the northern part of the Japan Sea Eastern Margin Mobile Belt. Previous studies have shown that many active submarine faults are located around Okushiri Island. These faults originally contributed to the expansion of the Japan Sea as normal faults, but have been reactivated as reverse faults since the Quaternary (Okamura, 2010). The Committee of
the Japan Sea (2014) investigated the continuities of active submarine faults that could act as the source of a tsunami based on existing geological surveys of the seafloor and obtained a rectangular model for the tsunami source faults. Tsunami source faults between F06 and F24 were observed in the offshore regions extending from North Tohoku to Hokkaido, which includes Okushiri Island. Among these faults is the epicentral area of the 1993 Hokkaido Nansei-Oki earthquake, which is located northwest of Okushiri Island (Fig. 1).

2.2. Wasabiyachi lowland

Okushiri Island has a long N–S trapezoidal shape with a perimeter of 84 km. The Wasabiyachi lowland is located north of the Aonae district at the southern end of Okushiri Island. The Wasabiyachi lowland is a narrow lowland area, with a depth of ~2 km and a width of 50–500 m and surrounded by an MIS 5c marine terrace that has an elevation of 20–30 m (Fig. 2; Miyoshi et al., 1985). The base of the marine terrace consists of marine mudstones and sandstones of Miocene to Neogene age (Miyoshi et al., 1985).
All of the coring sites were located on grassland (former paddy fields) at an elevation of 5 m and located ~300–500 m from the present coastline. The Aonae coastal sand dunes have an elevation of ~10 m and occur along the present coast of the Wasabiyachi River estuary (Hokkaido archaeological operations center, 2002). A beach ridge comprising ~5 m thick sand layers is located up to ~100 m landward of the sand dunes along the coast. Thus, the Wasabiyachi lowland is located in a topographic setting that is separated from the coast by sand dunes and a sandy beach ridge (Fig. 2). Further, the tidal level in Aonae at the southern end of Okushiri Island is ~40 cm at high tide. The tidal difference at Aonae is ~20 cm.

3. Materials and methods

3.1. Borehole sampling

Using a hand corer and excavating two pits, Kase et al. (2016) examined tsunami deposits in the surface layer (peat layer) of the Wasabiyachi lowland to 2–2.5 m
depths. Their results clarified the distributions of several layered tsunami deposits with ages of up to ~3,000 ka. In this study, we investigated deeper depths to observe tsunami records with ages of up to ~7,000-8,000 ka. A rotary corer and a rotating vibrational corer were used for the excavations. Each core had an internal diameter of 86 mm. Five core excavations were made (sites OKU-1–OKU-5). Site OKU-1 (42°4’3.70” N, 139°27’2.86” E, elevation 5.0 m) was located near the coast in the lowlands. Site OKU-2 (42°4’4.60” N, 139°26’59.38” E, elevation 4.9 m) is in the vicinity of the trial pit made by Kase et al. (2016). Site OKU-3 (42°4’6.80” N, 139°27’59.38” E, elevation 5.0 m) is located at the center of the lowland area. Sites OKU-4 (42°4’8.86” N, 139°26’59.77” E, elevation 5.2 m) and OKU-5 (42°4’10.29” N, 139°27’0.89” E, elevation 5.2 m) were located further inland (Fig. 2). The lengths of the cores collected from sites OKU-1 to OKU-5 were 23 m, 7 m, 25 m, 17 m, and 10 m, respectively. The OKU-1 and OKU-2 cores extended beyond the alluvium that constitutes the lowland strata and reached bedrock (Fig. 3).

3.2. Core analyses

The core samples were halved and the depositional facies were described and
photographed. Samples were collected for grain size and total sulfur (TS) analyses, as well as dating.

Samples were collected for grain size analysis every 0.5 cm in the thinly laminated clay layer, every 1 cm in the silt layer, and every 1 cm in the sand layers in the OKU-1 and OKU-3 cores. Samples were also collected every 1 cm in the sand layers in the OKU-2, OKU-4, and OKU-5 cores. Samples were not collected from the humus layers in any of the cores. The samples were pre-treated with a 10% hydrogen peroxide solution to remove organic matter. Grain sizes were measured using a Mastersizer 3000 laser diffraction-type grain size analyzer (Malvern Panalytical Ltd.).

The samples used for total sulfur analyses were muddy sediments from the OKU-2 core (2.6–20.0 m depth) at intervals of 20 cm and with a sample thickness of 1 cm. The samples were analyzed using an EMIA-120 sulfur analyzer (Horiba Ltd.).

Plant fragments were dated to obtain the corresponding layer ages using accelerator mass spectrometry (AMS) at the Accelerator Mass Spectrometry Co., Ltd. (Shirakawa City, Fukushima Prefecture). The IntCal 20 (Reimer et al., 2020) database of plant fragments and peaty samples and the OxCal v4.4.2 calibration program (Bronk
Ramsey, 2009) were used to calculate the calibrated ages (Table 1). As a reference, two
samples were also dated (at Accelerator Mass Spectrometry Co. Ltd.) using shell pieces
and the data were corrected using a Marine 20 (Heaton et al., 2020) database (Table 1).

In addition, we also recalculated the calibrated radiocarbon ages of eight
samples collected by Kase et al. (2016) from the Wasabiyachi lowland using the IntCal
20 database and the OxCal v4.4.2 calibration program (Table 2).

4. Results

4.1. Depositional facies

The OKU-1 and OKU-5 cores were divided into eight depositional facies,
excluding the uppermost topsoil and the basement bedrock (Fig. 3). In addition, well-
sorted sand layers, which indicate a depositional process that is distinctly different from
that of the regular depositional environment, were recorded separately as event deposits.

4.1.1. Facies FL1
A gravelly facies was observed in the lower layers of three cores (OKU-1: 16.0–22.1 m depth, OKU-3: 20.0–25.0 m depth, OKU-4: 16.0–17.0 m depth). This depositional facies comprises a fine to medium-grained gravel layer and a partially organic silt layer. The gravel is poorly sorted and contains many light gray to green-gray silty gravel that originated from the bedrock. The matrix of the gravel layer consists of gray sandy silt and poorly sorted fine to medium-grained sand. The organic sandy silt layer includes poorly sorted silty gravel of granule size.

4.1.2. Facies FL2

This facies was observed in the lower part of two cores (OKU-3: 16.5–20.0 m depth, OKU-4: 14.6–16.0 m depth). It consists of a slightly poorly sorted organic sandy silt layer that is interbedded with a poorly sorted fine to medium-grained sand layer with a thickness of ~3–5 cm. The sandy silt layer may also contain a large amount of organic matter and may be interbedded with a thin layer of organic matter. In addition, the upper part of this facies consists of a ~50 cm thick poorly sorted sandy silt layer, including silty gravel with a granule to fine pebble size.

4.1.3. Facies FL3
A silty facies was observed in the upper part of three cores (OKU-2: 4.5–6.2 m depth, OKU-3: 3.0–5.0 m depth, OKU-4: 3.0–5.0 m depth). This facies consists of a gray–brown organic silt layer and a gray silt to sandy silt layer, wherein the bottom of the gray silt to sandy silt layer is interbedded with a thin layer of clayey silt.

4.1.4. Facies FL4

A peaty facies was observed in the upper part of all cores (OKU-1: 1.0–4.2 m depth, OKU-2: 0.9–4.5 m depth, OKU-3: 0.7–3.0 m depth, OKU-4: 0.5–3.0 m depth, OKU-5: 1.8–6.0 m depth). This facies consists of an upper dark brown peat layer and a lower dark brown to light brown organic silt layer. This facies also includes undecomposed plant material. No bioturbation was observed.

4.1.5. Facies FL5

A silty was observed in the most upper parts of all cores (OKU-1: 0.4–1.0 m depth, OKU-2: 0.5–0.9 m depth, OKU-3: 0.2–0.7 m depth, OKU-4: 0.2–0.5 m depth, OKU-5: 0.3–1.8 m depth). This facies consists of a light brown to gray silt layer that contains plant matter, and a sandy silt layer. In core OKU-5, this facies is interbedded with a poorly sorted medium to coarse-grained sand layer with a thickness of 3–7 cm. No
bioturbation was observed.

4.1.6. Facies LG1

This facies was observed in the middle upper part of two cores (OKU-4: 5.2–6.2 and 12.9–14.5 m depth, OKU-5: 8.3–10.0 m depth). This facies consists of alternating gray silt and clayey silt layers. Only a small amount of bioturbation was observed. Some thin laminated layers were observed.

4.1.7. Facies LG2

This facies was observed in the middle upper part of four cores (OKU-1: 4.2–6.8 and 14.4–16.0 m depth, OKU-3: 5.0–10.8 and 13.8–16.5 m depth, OKU-4: 6.2–11.0 m depth, OKU-5: 6.0–8.3 m depth). This facies consists of a clayey silt layer in which a ~1 mm dark gray extremely fine-grained thinly laminated layer was observed, and is interbedded with a thin layer of clay or clayey silt with a thickness of < 5 cm.

4.1.8. Facies LG3

This facies was observed in the middle upper part of core OKU-3 (10.8–13.8 m depth). This facies consists of a clayey silt to clay layer in which a ~1 mm dark gray extremely fine-grained thinly laminated layer was observed.
4.1.9. Facies BA1

This facies was observed in the middle upper part of core OKU-1 (6.8–14.4 m depth). This facies consists of a well-sorted dark gray coarse to fine-grained sand layer with cross-bedding. The facies also has horizons that contain large amounts of light brown to gray silty gravel of granule to fine pebble size. This facies did not contain plant material.

4.3. Changes in grain size and total sulfur content in core OKU-3

We measured the total sulfur content and grain size of the muddy sediment in core OKU-3, collected from the center of the Wasabiyachi lowland, to clarify any changes in the depositional environment, while excluding the gravelly facies near the basement and the humus layer at the top. The median grain size (Md), geometric mean grain size (GM), mode grain size (Mo), and geometric standard deviation (Sorting) obtained from the grain size analysis are shown in Figure 4. The Md and Sorting characteristics are described below.
Md sizes of 10–40 μm were observed at depths of 16.5–20.0 m (FL2). Fine grains of 10–20 μm were observed at depths of 13.8–16.5 m (LG2). Slight variations of 10–30 μm were observed at depths of 10.8–13.8 m (LG3). Slight variations of 10–40 μm were observed at depths of 5.0–10.8 m (LG2), except for the sand layer. Sizes of 10–70 μm were observed at depths of 3.0–5.0 m (FL4), in which large size variations were observed (Fig. 4).

A Sorting of 3.3–4.5 was observed at depths of 16.5–20.0 m (FL2). A Sorting of 3.0–4.0 (max 4.8) was mainly observed at depths of 13.8–16.5 m (LG2). Variations of 2.8–5.8 were observed at depths of 10.8–13.8 m (LG3). Slight variations of 3.3–4.8 were observed at depths of 5.0–10.8 m (LG2), except for the sand layer. A Sorting of 3.4–4.5 was observed at depths of 3.0–5.0 m (FL4; Fig. 4). The Md and Sorting values of the event deposits in cores OKU-1 through OKU-5 are described in section 4.3.

SO$_4^{2-}$ in water becomes H$_2$S owing to the action of sulfate-reducing bacteria and is solidified in sediments as FeS$_2$ (via FeS). Accordingly, the total sulfur content of the sediment indicates the contribution of seawater to a body of water, as well as the reducing capacity of the depositional environment. Core OKU-3 had a total sulfur content
of ~0.5 wt.% at depths of 16.5–20.0 m (FL2). While variations were observed, at depths of 13.8–16.5 m (LG2) the total sulfur content was ~2.0 wt.%.

At depths of 10.8–13.8 m (LG3), the total sulfur content was ~3.0 wt.%. At depths of 5.0–10.8 m (LG2), the lower and upper portions had total sulfur contents of 5.0 wt.% and 2.0 wt.%, respectively. At depths of 3.0–5.0 m (FL4), the total sulfur content varied from 0.8 to 4.0 wt.%. The results indicate an overall total sulfur content of ~0.5% between the deepest section and 16.5 m, excluding the data at 17.1 m (Fig. 4).

4.2. Core sample age model

The radiocarbon ages of a total of 50 core samples were determined using plant material, peaty sediment, and shell fragments (Table 1). All of the radiocarbon ages conformed to the stratigraphic succession of each core. The ages of the horizons in each core were estimated based on the interval sedimentation rates and the horizons for which radiocarbon ages were obtained. Sedimentation rates were calculated for the upper and
lower ranges of the calibrated ages (2σ). The thicknesses of the event deposits were excluded from the interval sedimentation rate calculations because their deposition occurred rapidly (Fig. 5).

4.3. Event deposits

The sand layers observed in all cores were interbedded with the peaty layers and muddy sediment, except for the gravel observed at the bottom of the cores (Figs. 3 and 4). A distinct boundary was also observed between the upper and lower facies of the sand layers. This indicates that the sand layers were formed by a process different from the typical depositional process in this environment. In this study, we defined an event deposit as sediment with multiple characteristic facies, including basal erosion, abrupt changes in grain size or degree of sorting, contamination with heterogeneous particles such as plant fragments or mud clasts, and containing sedimentary structures such as parallel or cross-lamination (Table 3).
In core OKU-1, which was located closest to the coast, 16 event deposit horizons were observed to a depth of 6.0 m (Fig. 3; Table 3). The upper three horizons were fine to very fine-grained or fine to medium-grained sand layers with thicknesses of 10–40 mm, while the lower horizons were well-sorted coarse to medium-grained sand layers with thicknesses of 100 mm to more than 300 mm. Core OKU-2 had a shallower bedrock depth compared to the other sites, with an alluvium thickness of ~6.2 m. Thirteen event deposit horizons were observed in this core. While these event deposits included some sand layers with thicknesses of 100 mm at horizons < 2.0 m deep, they consisted of well-sorted fine to medium-grained sand layers with thicknesses of ~5–20 mm. Some thin (7–50 mm) layers were observed at horizons deeper than 2.0 m, but these were composed of well-sorted fine to medium-grained sand layers with thicknesses of 150–340 mm (Fig. 3; Table 3). Fourteen event deposit horizons were observed in core OKU-3. While these event deposits were composed of well-sorted medium-grained sand layers with thicknesses of 4–30 mm, the horizons observed at depths of 7.79–10.4 m were interbedded with a thick (270–1,400 mm) medium-grained sand layer (Figs. 3, 4 and 6; Table 3). Eight event deposit horizons were observed in core OKU-4. These event
deposits were composed of well-sorted medium-grained sand layers with thicknesses of 4–210 mm, the horizons observed at depths of 8.0–8.7 m were interbedded with a coarse to medium-grained sand layer with a thickness of 600 mm (Fig. 3; Table 3). Ten event deposit horizons were observed in core OKU-5, which was the site located furthest inland. While these event deposits were interbedded with well-sorted medium to coarse-grained sand layers with thicknesses of 20–190 mm, the horizons at depths of 8.6–9.3 m were interbedded with a well-sorted medium to coarse-grained sand layer with a thickness of 600 mm (Fig. 3; Table 3).

5. Discussion

5.1. Depositional environments

Facies FL1 consists of very poorly sorted granule to fine pebble layers and slightly sandy silt layers. The organic sandy silt layers also include silty gravel with a fine gravel size, and are poorly sorted. Facies FL2 consists of slightly poorly sorted sandy silt
layers and is interbedded with a thin layer of poorly sorted fine to medium-grained sand layers. The sandy silt layer contains large amounts of organic matter. These poorly sorted gravel deposits, silty gravel, and turbidites that contain organic material indicate a depositional environment that was affected by fluvial processes. Intercalated silty and coarse sand layers indicate that deposition occurred in a small river channel and floodplain. The facies succession and sedimentary features indicate that facies FL1 and FL2 represent a fluvial depositional environment (Miall, 1992).

Facies FL3 consists of organic silt and sandy silt layers, while facies FL4 comprises organic silt and peat layers that contain undecomposed plant material. No bioturbation was observed in either of these facies. Organic turbidites with no observed bioturbation and peaty layers containing undecomposed plant material are indicative of a freshwater swamp environment (Miall, 1992). In both of these facies, it is possible that the fluvial channels were undeveloped swamps, as these facies did not include interbedded sand layers.

Facies FL5 consists of silt layers that contain plant material and sandy silt layers, and is interbedded with poorly sorted coarse-grained sand layers at the landward sites. As
no bioturbation was observed and the facies contained thin layers of coarse-grained sand. 

this depositional facies represents a small fluvial channel and floodplain depositional 
environment (Miall, 1992).

The total sulfur content of the turbidites in facies FL2 and FL3 in core OKU-3 were < 1 wt% (Fig. 4), indicating a non-reducing depositional environment that was not 
affected by seawater. The depositional environment determined from the depositional 
facies is consistent with implications of the total sulfur content.

Facies LG1–LG3 consist of thinly laminated clayey silt and silt layers. The 
thinly laminated layers in LG2 and LG3 represent a typical lake environment where 
surface disturbances do not extend to the bottom of the lake. The lack of bioturbation and 
burrows also indicates a closed and reducing environment (Strum, 1979). LG2, which 
contained a particularly thinly laminated interval, suggests that reducing conditions 
persisted at the bottom. LG1 also contained silt, but some bioturbation was also observed. 
This suggests that the water depth decreased and the number of aquatic organisms 
increased. The succession and sedimentary features of these facies indicate a coastal 
lagoon depositional environment. These facies also provide evidence for the
development of a coastal sand barrier that separated the Japan Sea (Aonae Bay) from an inland lagoon.

Facies BA1 consists of well-sorted coarse to fine-grained sandy layers that contain cross-bedding structures. Well-sorted sand layers indicate a depositional environment that was strongly affected by a wave environment (Reinson, 1984). Beach ridges that include sand dunes and ridges are located between the current Wasabiyachi lowland and the Japan Sea, thereby blocking the Wasabiyachi lowland estuary. Because of the differences between the depositional facies of the current environment and that of the inland lagoon environment, BA1 may represent the coastal sand barrier depositional environment.

5.2. Wasabiyachi lowland depositional processes

We investigated the alluvium formation in the Wasabiyachi lowland based on changes in the depositional facies and sediment ages in the cores. At the OKU-2 site, bedrock was reached at 6.2 m. Meanwhile, the bases of the alluvium aggrading the lowlands at sites OKU-1, OKU-3, and OKU-4 can be estimated as over 20–25 m deep.
Thus, the valley formation of the Wasabiyachi lowland occurred near sites OKU-1 through OKU-5 (Fig. 3). Fluvial material containing coarse gravel deposits (FL1 and FL2) were deposited ~9.5 ka. As sea level increased since the last glacial period near the Japanese archipelago, sites OKU-1, -3, and -4 changed rapidly to a lagoon environment, suggesting the presence of brackish water 8.5 ka. Moreover, as deposits that indicate a lagoon environment were obstructed in horizons at 14.4–16.0 m deep in core OKU-1, it is possible that a coastal barrier had already formed seaward of the surveyed area (Fig. 3). Since then, the obstructed lagoon environment expanded landward until ~5.700 ka at the OKU-5 site in the valley, and until ~5.2 ka at the seaward OKU-1 site. The depositional environment of this lagoon had a total sulfur content of 2–5 wt.% in the deposits, indicating that it was heavily obstructed and hosted a strongly reducing environment. Facies LG3 (~7–7.3 ka) was observed at depths of 11.0–14.0 m in core OKU-3 (Figs. 3 and 4). This indicates that the lagoon environment was at its most closed at ~7–7.3 ka. Moreover, the change in lagoon facies (from LG1 to LG3) indicates the early stages of lagoon formation, the progression of aggradation, and the differences in lagoon water depths from seaward to landward.
Based on the facies observed in core OKU-1, the coastal barrier of the Wasabiyachi lowland (estuary) was estimated to have formed ~8.5 ka. Furthermore, due to the observed barrier deposits at depths of 6.8–14.4 m in core OKU-1, the estuary barriers can be estimated to have developed at ~6–7.5 ka, then moved seaward thereafter (Fig. 3).

At ~5.2 ka, aggradation of the entire lagoon progressed, altering the lagoon into a freshwater-affected floodplain lowland (FL3) and a lowland with peat development. Since 2 ka, the peaty lowlands have been altered to slightly dry land on the inland side (and at some sites), and have become fluvial floodplains.

Accordingly, using inferences from facies changes in the cores and the current topographic environment, the Wasabiyachi lowland is a depositional environment that has been obstructed by coastal barriers in the estuaries from ~8.5 ka until the present. The deposits of this obstructed depositional environment are interbedded with deposits (sand layers) that suggest the events described above.

5.3. Event deposit ages, correlations, and facies changes
At the study sites, the facies interbedded with event deposits were obstructed lagoons, muddy floodplains, and peat deposits. We determined the ages (age ranges) of the bases of the event deposits observed in each core (Table 3), assuming that the sedimentation rate for each of these facies was generally constant. Among these, the sedimentary ages matched within the age range for which the sedimentation is apparent, and the comparable event deposits at the coring sites were named OW-4 to OW-20, thereby referencing the deposit depth and facies characteristics (continuity of deposits that indicate thick layers). Among these, event deposits OW-4 and OW-5 matched those identified as tsunami-induced event deposits by Kase et al. (2016).

Among the event deposits interbedded in the cores, lateral changes in layer thickness and particle size (Md and sorting) are shown in Figure 7 for deposits OW-4, -5, -8, -9, -10, -12, -13, and -14, which are comparable in cores from three or more sites. In general, sand layers with a thickness of 10 cm or more had different individual particle size changes (as observed in the Md), but commonly exhibited upward fining. Sand layers that were thick and could be divided into multiple units often exhibited upward fining in each unit. The sorting of the sand layers and units with thicknesses of 10 cm and greater
occurred at many sites, with large variations. However, in some cases, the sorting tended
to worsen upward, owing to upward fining (Fig. 7).

Among the comparable event deposits, OW-5, OW-8, and OW-13 contained
sand layers that were thicker at the OKU-1 site near the coast and became thinner toward
the OKU-4 and OKU-5 sites on the landward side. Furthermore, the Md of core OKU-1
was 300–400 μm, but became 200–250 μm landward, indicating fining. In particular,
the Md of OW-13 in core OKU-5 underwent a sudden change in fining. Meanwhile, the
sorting of these event sand layers was ~2-3 in core OKU-1 and ~3 on the landward side,
indicating that sorting did not change as much as Md. In addition, the sorting became
slightly worse as the layers thinned and grains became finer landward. These changes
indicate that sorting may have worsened due to the incorporation of fine terrigenous
particles as they flowed upstream (inland). The sand layer in OW-14 has a thickness of
~20 cm in core OKU-1, but became thicker in core OKU-3, and multiple units were
observed. The layer thickness decreased by half landward. The Md was 280–360 μm in
cores OKU-1 and OKU-3, suggesting upward fining. In contrast, the Md in cores OKU-
4 and OKU-5 sites were ~250–370 μm and 230–320 μm, respectively, and exhibited
slight fining. However, the upward fining in each unit was unclear, and large variations were observed throughout. Sorting also tended to become poor, as large variations were observed at the landward sites (Fig. 7).

Overall, for each event deposit, the layer thicknesses generally became thinner and the grains tended to become finer landward. For reference, the Md of the sand layer at the present beach (foreshore environment) of the Wasabiyachi lowland estuary is 270–340 µm, which is similar to the Md of the event layers in cores OKU-1 and OKU-2 near the coast. In addition, the sorting of the present beach sand is ~1.4, which is better sorted than the event sand layers. The lack of uniform event deposit layer thicknesses and grain sizes with distance from the ocean indicates differences due to water mass speed during an event, as well as differences in water depth in the depositional area (microtopography of a lagoon or floodplain).

5.4. Event deposit origin
Kase et al. (2016) conducted hand boring and dug trial pits up to ~2 m in depth, obtaining event deposits at five horizons (Ow-1 to Ow-5). The characteristics of these event deposits included the following: 1) the layers become thinner and the grains become finer landward; 2) they had a grain size composition similar to that of beach sand; 3) the grain fabric of the sand layer indicated a landward paleo-flow direction; and 4) marine dinoflagellate cysts and foraminiferal linings were present in the sand layer. In addition, since the Wasabiyachi lowland has not experienced any flood damage from storm surges or tsunamis in the last 300 years, we can conclude that the origin of these event deposits was multiple tsunamis that occurred over time. Based on radiocarbon dating of the deposits, the age of Ow-1 was 0.7–1.0 ka, Ow-2 and Ow-3 were 1.7–1.9 ka, Ow-4 was ~2.6 ka, and Ow-5 was ~3.0 ka. Kawakami et al. (2017a, b) re-investigated the tsunami history of the entire Okushiri Island (including the Wasabiyachi lowland) and named the tsunami deposit caused by the sector collapse on Oshima-Oshima in 1741 as OK-1, Ow-1 of Kase et al. (2016) was named OK-2, Ow-2, and Ow-3 were named OK-3 (~1.5 ka), and Ow-4 and Ow-5 were named OK-4 and OK-5, respectively. OW-4 and OW-5 in the present study correspond to Ow-4 and Ow-5 in the Kase et al. (2016) study, and OK-4
and OK-5 in the Kawakami et al. (2017a, b) studies, respectively. Note that the radiocarbon dating calculations conducted by Kase et al. (2016) were revised according to IntCal 09 (Raimer et al., 2009), and have since been recalculated according to IntCal 20 (Raimer et al., 2020). As a result, the difference in the calibration ages (2σ) according to IntCal 09 and IntCal 20 is approximately 10 to 80 years, which does not constitute a major change to the chronological outline for Ow-1 to Ow-5 that was established previously.

Overall, events deposits OW-6 to OW-20 exhibited thinner layers and finer grains landward. In addition, the grain size composition of the sand layers interbedded at seaward sites OKU-1 and OKU-2 were similar to those of the current beach sand. This strongly suggests that the sand layers between OW-6 and OW-20 were derived from the sea, and not inland regions. In addition, the sand layers of the lower deposits (OW-13 to OW-20) were interbedded with the muddy sediment of an obstructed lagoon environment. This lagoon deposit contains extremely thin laminated facies with no bioturbation, indicating the presence of a closed lagoon in which sand layers that originated in the river have not been transported. In contrast to this depositional environment, the sand layers
between OW-13 and OW-20 indicate that they were transported to the lagoon over the
beach ridges that developed along the coast. The upper deposits (OW-6 to OW-12) are
interbedded with peat layers and muddy lowlands in a similar manner to Ow-4 and Ow-5. The sand layers in these deposits (OW-6 to OW-12) have not been examined for marine
microfossils, as in Kase et al. (2016). However, these sand layers were interbedded in a
depositional environment in a similar manner to Ow-4 and Ow-5, suggesting that the
process of sand layer formation was the same. Accordingly, it is likely that event deposits
OW-6 to OW-20 observed in this study are tsunami deposits caused by tsunamis beyond
the beach ridges that have been surmised to have been present between the Wasabiyachi
lowland and the coast.

5.5. History of tsunami events and potential tsunami sources

Kase et al. (2016) and Kawakami et al. (2017a, b) surveyed tsunami deposits in
the coastal lowlands of Okushiri Island and in the Hiyama region of Hokkaido. On
Okushiri Island, five horizons (OKU-1 to OKU-5) were observed in peat layers that are
~3,000 years old. Two horizons (HY-1 and HY-2) were also observed in the Hiyama
region. In addition, turbidite layers at four horizons (ST-1 to ST-4) were observed in the Shiribeshi Trough off the coast of Hokkaido, which have been established as turbidites that originated from an earthquake (Shimokawa and Ikehara, 2002). Among these, OK-1, HY-1, and ST-1 are tsunami deposits that were caused by the sector collapse on Oshima-Oshima in 1741 (Satake, 2007; Satake and Kato, 2001), whereas OK-2, HY-2, and ST-2 are deposits caused by tsunamis ~800 years ago. In addition, it has been suggested that OK-5 and ST-3 are sediments produced by a tsunami ~3,000 years ago.

According to previous studies, tsunami records in the Japan Sea off the southwestern coast of Hokkaido contain only six horizons that extend to ~3–3.5 ka, including the ST-4 event observed in the Shiribeshi Trough (~3.5 ka; Kawakami et al., 2017a, b).

Of these previously identified horizons, the tsunami event ~800 years ago may have been generated by F17 or F18 in the fault model by the Committee of the Japan Sea (2014), based on similarities with the distribution of sedimentation caused by the 1741 tsunami (Kawakami et al., 2017) and source fault estimates based on numerical calculations (Ioki et al., 2019). Thus, few studies of tsunami occurrence and their source faults have been conducted in the Japan Sea off the southwestern coast of Hokkaido.
In this study, we clarified the history of tsunami deposits on Okushiri Island and extended the record to ~7.6 ka (Fig.3 and Table 3). Until now, tsunami records in the northern Japan Sea from ~7 to 8 ka have only been observed in Lake Kamo, Sado Island, Niigata Prefecture, and in the old Iwafune Lagoon in Murakami City, Niigata Prefecture (Urabe, 2017). Future studies should compare the tsunami records and estimated tsunami sources for Okushiri Island, Hokkaido, and Sado Island, Niigata Prefecture.

6. Conclusions

In this study, an extended coring survey was conducted in the Wasabiyachi lowland on Okushiri Island, southeast of Hokkaido. Since beach ridges formed between the Wasabiyachi lowland and the coast at ~8 ka, peaty lowland deposits have been continuously deposited in closed lagoons. Such topographical/geological environments are suitable for examining tsunami records that are much older than those researched to date. As a result, 17 deposits (OW-4 to OW-20) produced by offshore tsunamis were identified, and their ages were estimated. The results of this study can be used to contribute to the tsunami occurrence history of the northern part of the Japan Sea and the
analysis of potential source faults located offshore of NE Japan.

**Declarations**

**Ethics approval and consent to participate**

Not applicable

**Consent for publication**

Not applicable

**Availability of data and materials**

Not applicable

**Competing interests**

There are no competing interests in relation with the present research.

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Authors’ contributions

AU and YK contributed to writing the main part of the paper and re-correction of age dating. AU, YK, GK, and NK did geological survey and borehole sampling. YT carried out grain size analysis and sedimentological interpretations. HM and FH carried out grain size and total sulfur quantity analyses.

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Figure and table captions

Figure 1  Distribution of the active faults in the offshore between Aomori to Hokkaido, northern part of Japan Sea (Committee for Technical Investigation on Large-Scale Earthquakes in the Sea of Japan, 2014). Okushiri island is located at the offshore of southwest Hokkaido, and active faults is distributed over the surrounding sea. Large earthquake (1983 Middle Japan Sea earthquake and 1993 Hokkaido Nansei-Oki earthquake) occurred in this area.

Figure 2  Topography around the Wasabiyachi lowland, Aonae region, southern part of Okushiri island. Index map shows the localities of borehole sites. Geologic and geomorphologic classification of landforms is based on Hata et al. (1982) and Koike and Mchida (2001). The Wasabiyachi lowland along the Aonae Bay is barriered by Holocene marine terrace and coastal beach ridge with sand dune. Contour maps are reproduced from online map of the Geospatial Information Authority of Japan (GSJ).
Seventeen event deposits (tsunami sand beds: OW-4 – OW-20) are well correlated in the Wasabiyachi lowland (see Figure 2 for location).

Figure 4  Vertical changes of grain size analysis and content of total sulfur of the OKU-3 core. The grain size analysis showed Md (median grain size), G.M. (geometric mean grain size), Mo (mode grain size) and sorting (geometric standard deviation) in the figure.

Figure 5  Age-depth curve of the OKU-1 – OKU-5 cores with estimated ages of event deposits. The vertical axis of the graph shows the depth and thickness of event deposits. The horizontal axis shows the calibrated age value to clearly indicate the correlation of the event deposits.

Figure 6  Photograph of lithofacies and event deposits in depth 0 – 15 m of the OKU-3 core. The event deposits are consisted of well-sorted sand layer. The lithofacies of
event deposits are clearly different from the steady depositional environment.

The facies code of LG2 and LG3 show laminated silt and clay-silt of occlusive lagoon. The FL4 and FL5 show peaty environment of fluvial floodplain. The Ko-d (AD 1640 Komagatake-d tephra) is widely distributed in the southern part of Hokkaido, and this tephra is compared in the Okushiri area (Kase et al. 2016 and Kawakami et al. 2017a).

Figure 7  Stratigraphic correlation and changes of lithofacies, Md (median grain size), and sorting (geometric standard deviation) of the event deposits (OW-4, -5, -8, -9, -10, -12, -13, and -14).

Table 1  $^{14}$C age summary of the OKU-1 to OKU-5 cores. Age ranges are calibrated using IntCal 20 and Marine 20.

Table 2  $^{14}$C age dating of the Wasabiyachi lowland reported by Kase et al. (2016). Kase et al. (2016) carried out the age calibration using IntCal 09. In this study, the $^{14}$C
ages carried out re-calibration using IntCal 20.

Table 3  Description of lithofacies and estimated age of the event deposits for the OKU-

1 to OKU-5.
Figure 1

Distribution of the active faults in the offshore between Aomori to Hokkaido, northern part of Japan Sea (Committee for Technical Investigation on Large-Scale Earthquakes in the Sea of Japan, 2014). Okushiri island is located at the offshore of southwest Hokkaido, and active faults is distributed over the surrounding sea. Lage earthquake (1983 Middle Japan Sea earthquake and 1993 Hokkaido Nansei-793 Oki earthquake) occurred in this area.
Figure 2

Topography around the Wasabiyachi lowland, Aonae region, southern part of Okushiri island. Index map shows the localities of borehole sites. Geologic and geomorphologic classification of landforms is based on Hata et al. (1982) and Koike and Mchida (2001). The Wasabiyachi lowland along the Aonae Bay is barriered by Holocene marine terrace and coastal beach ridge with sand dune. Contour maps are reproduced from online map of the Geospatial Information Authority of Japan (GSJ).
Figure 3

Geological log of the OKU-1 - OKU-5 cores, 14C ages and event deposits. Seventeen event deposits (tsunami sand beds: OW-4 – OW-20) are well correlated in the Wasabiyachi lowland (see Figure 2 for location).
Figure 4

Vertical changes of grain size analysis and content of total sulfur of the OKU-3 core. The grain size analysis showed Md (median grain size), G.M. (geometric mean grain size), Mo (mode grain size) and sorting (geometric standard deviation) in the figure.
Figure 5

Age-depth curve of the OKU-1 – OKU-5 cores with estimated ages of event deposits. The vertical axis of the graph shows the depth and thickness of event deposits. The horizontal axis shows the calibrated age value to clearly indicate the correlation of the event deposits.
Figure 6

Photograph of lithofacies and event deposits in depth 0 – 15 m of the OKU-3 core. The event deposits are consisted of well-sorted sand layer. The lithofacies of event deposits are clearly different from the steady depositional environment. The facies code of LG2 and LG3 show laminated silt and clay-silt of occlusive lagoon. The FL4 and FL5 show peaty environment of fluvial floodplain. The Ko-d (AD 1640 Komagatake-
d tephra) is widely distributed in the southern part of Hokkaido, and this tephra is compared in the Okushiri area (Kase et al. 2016 and Kawakami et al. 2017a).

Figure 7
Stratigraphic correlation and changes of lithofacies, Md (median grain size), and sorting (geometric standard deviation) of the event deposits (OW-4, -5, -8, -9, -10, -12, -13, and -14).

Supplementary Files
This is a list of supplementary files associated with this preprint. Click to download.

- Table1urabe.xlsx
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